NASA TECHNICAL TRANSLATION NASA TT F-16201

WIND MOTORS: THEORY, CONSTRUCTION, ASSEMBLY AND USE IN DRAWING WATER AND GENERATING ELECTRICITY

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(NASA-TT-F-16201) WIND MOTORS: THEORY, CONSTRUCTION, ASSEMBLY AND USE IN DRAWING WATER AND GENERATING ELECTRICITY (Kanner (Leo) Associates) N75-19821
CSCL 10A Unclas
G3/44 13471

Translation of "Théorie, construction, montage, utilisation au puisage de l'eau et à la production de l'électricité," Paris, Dunod Publishers, 1933, 270 pages

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 APRIL 1975

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STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TT F-16201		
4. Title and Subtitle WIND MOTORS: THEORY, CONSTRUCTION, ASSEMBLY AND USE IN DRAWING WATER AND GENERATING ELECTRICITY		5. Report Date April, 1975 6. Performing Organization Code
7. Author(s) R. Champly		8. Performing Organization Report No. 10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11. Contract or Grant No. NASw-2481 13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington D. C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Théorie, construction, montage, utilisation au puisage de l'eau et à la production de l'électricité," Paris, "Dunod" Publishers, 1933, 270 pages

16. Abstract After a brief consideration of the history of windmills, various models are described in detail, with discussions of their pros and cons, especially in regard to number of blades and method of orientation to the wind. Systems for transmission of power from the wind motor to a pump, generator, or other type of equipment are described. A method for computing the tension and compression stresses on the wind motor pylon is given and the construction of pylons and water tanks is discussed. Foundation and anchoring systems are described, as are several methods for assembling and raising the wind motor on its pylon. Systems using wind motors to draw and elevate water by means of pumps and systems using wind motors in conjunction with generators, storage batteries, etc., to generate electricity are described in detail, and efficiency tables and comparative cost price tables are provided for each of these applications.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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PREFACE

Wind is a free form of motive power which occurs over the entire surface of the earth. Unfortunately, this power is irregular and inconstant, it sometimes becomes destructive, and it is impossible to regulate it by means of accumulating reservoirs, as can be done with waterfalls.

Although devastating hurricanes are a rare occurrence, nevertheless, due to their probability, the construction of devices using wind must be extremely solid, which greatly increases their cost price.

Despite these drawbacks, the use of wind power is to advantage, especially in countries without waterfalls, coal or oil. In Denmark, where this is the case, the importance of this problem has been understood, and in 1891, the King of Denmark assigned the French professor Paul La Cour the task of determining the optimum principles for the design and use of wind motors and their application to the production of electricity.

For this purpose, a testing station in Askov was placed at his disposal, under a generous annual subsidy.

In 1900, Professor La Cour had already obtained positive results. He wrote:

"The establishment of the Askov testing station is a unique phenomenom. One may find it surprising that a small country like Denmark, taking a bold step ahead of any others, is willing to devote such large sums of money to research on the use of wind power. Nothing could be more natural, however, considering that this country, which has no waterfalls or coal, is exposed to the risk of paying increasingly high rates for the purchase of fuel from foreign countries at a time when the range of uses for machines and the cost of raw materials are simultaneously increasing."

Mr.La Cour's main proposal was to supply energy for agricultural uses, and in Askov he gave one-week courses to farmers to familiarize them with the operation of wind motors and electrical devices.

This book will be concerned with the work of Professor La Cour.

France has a plentiful supply of waterfalls and coal, although the use of wind motors would help to conserve these resources. It is the French colonies, however, which have the greatest interest in building windmills: there are already a great many in Algeria, Tunisia, Morocco and elsewhere. However, the number of these installations is not comparable to the number in America, where wind motor contractors are mass producing thousands of units, which are selling rapidly.

One project which should not be delayed would be to set up signaling posts, along main aircraft communication lines or desert crossings, for example; these posts would each consist of a wind motor, a generator, a storage battery and a beacon which would be illuminated automatically every night by a mechanism which would be easy to design. This would be wonderful propaganda for wind motors.

From the standpoint of supplying drinking water to cities and communities, wind motors have heavy advantages. This is due to the fact that the French government gives communities who have been wanting to set up a water supply a subsidy for the installation of machines and piping, but offers no financing for the fuel or electricity which will operate these machines.

Here the windmill would be ideal, since once it has been installed it does not consume power in any form and its annual maintenance is quite minimal. This is why a number of communities are now building these highly advantageous systems.

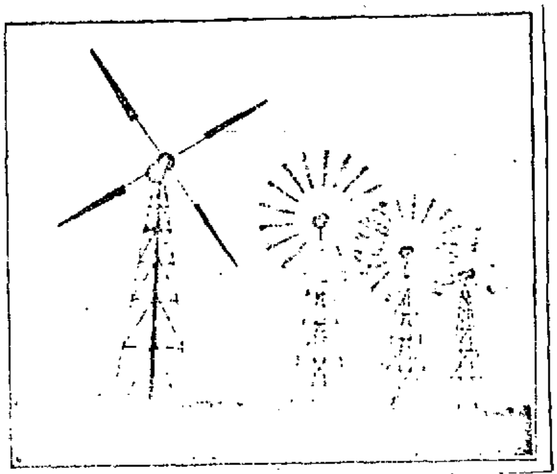
At any rate, it is to be regretted that the few windmill builders in France, who produce excellent systems, are not encouraged by the government or backed by a large financial outlay permitting inexpensive mass production.

From a technical standpoint, there has been no work in France which has collected all the documents and results gained in this area. This is why we have assembled and coordinated, everything we have been able to find to the best possible extent, with the hope that our book will facilitate the discovery of improved methods for capturing wind power.

Mr. Constantin, engineer and constructor of air-powered systems, Mssrs. Darrieus and G. Lacroix, engineers with the Electro-Mechanical Company, and Mr. Verdeaux, Engineer of Skills and Manufacturing, have provided me with scientific research whose value may be judged by the reader; my sincere thanks to these engineers.

We should mention the wind wheel testing and comparison station installed by the Cyclone Companies close to Compiégne (Oise). Figure 1 is a photograph of this station.

Fig. 1.



WIND MOTORS: THEORY, CONSTRUCTION, ASSEMBLY AND USE IN DRAWING WATER AND GENERATING ELECTRICITY

R. Champly

Chapter 1. History

Windmills are of very ancient origin. The four-blade Dutch windmill is generally believed to be the predecessor of those currently being built, but this is in error, since windmills were known earlier still in the Orient. /1*

In his History of the Caliphs, Washington Irving states that a certain Firus, made prisoner by the Persians in about 634 AD, complained to the caliph Omar of the heavy taxation which had been imposed upon him.

The caliph visited Firus's home and saw that the latter, who was a carpenter, had built a windmill.

France was the first country in Europe in which windmills were built, by one Mabillon in 1105. From France the windmill spread to England, and in 1332, Bartolomeo Verde introduced them in Italy.

The Dutch windmill was invented around the year 1650, probably by a Flemish carpenter.

These origins of the windmill have been outlined by the Lykkegaard Wind-Mill Manufacturing Company of Copenhagen (Denmark).

In around 1840, Berton, a mechanic in Chapelle-Saint-Denis, close to Paris, improved the blades of earlier windmills by replacing the canvas with long fir battens, parallel to the axis of the blade, which folded back on each other like a bird's feathers or the blades of a fan during hurricanes. A model of this windmill is in the Conservatoire des arts et métiers [Conservatory of Arts and Crafts] in Paris.

These battens were folded or expanded by means of a hand-powered rack and pinion mechanism, and later on by an automatic system. /2

This windmill had four blades and the configuration of the old Dutch windmill with pivoting roofing for orientation.

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* Numbers in the margin indicate pagination in the foreign text.

On March 23, 1842, Amédée Durand, a Parisian mechanic, presented to the Academy of Sciences a report on a wind motor mounted on a pylon made up of four wooden planks. This windmill had six sails with canvas blades which were quite similar to the so-called "brigantine" sails of ships. These blades were oriented to face into the wind, or they were allowed to float in the direction of the wind during storms, by means of cables termed "sprits" which were automatically controlled by a counterweight. The orientation of the device was also automatic.

A description and drawings of the Berton and Durand devices may be found in the fourth volume of <u>Cours d'agriculture</u> [A Course in Agriculture] by Nadault de Buffon, published in 1858 by Victor Dalmont, Paris, pages 212-222. The extensive report made to the Academy of Sciences on the Durand wind motor may also be found there.

Later on this inventor substituted wooden paddles for his canvas blades, and a large number of these motors were used to pump water.

This invention was taken up by the Americans, who made a number of improvements and built numerous copies with a large number of sheet steel blades and automatic orientation and regulation.

The Danish built excellent models with a small number of blades per wheel (four or five).

In France, a number of constructors have undertaken the manufacture of wind turbines and have made improvements in them. These will be mentioned later on, as will be the turbines of Bollée and A. Dumont, which are based on specialized principles.

The Durand windmill, with its wooden paddles, already swiveled by means of a rudder, folded back under storm winds and was brought back into position by springs. Thus it opened a wide field for development along these lines.

With regard to the advances made in France during the initial use of air turbines, in his <u>Aide-mémoire des ingénieurs</u>, [Memorandum for Engineers], 1892 edition, page 384, J. Claudel notes that Herpin had supervised the development of a four-blade windmill of the Berton system in the Indre department. Each blade was composed of 11 fir planks 1[illegible] cm thick, 25 cm wide and 8 m long, folding in the manner of a parallelogram. /3

This windmill drove three pairs of millstones, one in a sawmill, one in an oilworks, and one for a wheat thresher; it produced 2000-2500 hectoliters of ground wheat per year.

There were four windmills on exhibit at the Paris Exposition of 1867; these were discussed in a report by Mr. Lebleu, Mining Engineer, which may be found in Debauve's Manuel de l'Ingénieur [Engineer's Manuel] (Dunod), from which the following is taken:

Lepaute Mill. Construction begun in 1858; two discs with veins 3 m in diameter, with 16 wooden blades each. Each disc controlled a chain pump to raise water.

Mahoudeau Mill. Wheel with six blades, each three meters long, slightly inclined into wind. Total area of blades: ten square meters. The canvas blades were supported at their free end by a flexible spring-activated blade which allowed the canvas to incline automatically when the wind became too violent. Swiveling was automatic.

Formis Mill. Invented by Dellon, Engineer of Bridges and Causeways. The canvas blades were triangular and were supported by yards which inclined when the wind was too strong, and were then returned to position by a counterweight. There were eight blades on the wheel.

This device was used to drain marshes between Montpellier and Séte, and withstood the mistral quite satisfactorily.

Thirion Mill. Built by the Châtelineau Company. This mill had 20 wooden blades in the form of a narrow sector able to pivot on one of its radii. The regulatory system was based on centrifugal force: this consisted of counterweights which moved away from the horizontal shaft when the windmill turned too quickly, and made the blades pivot to a position parallel to the direction of the wind.

The Thirion and Formis systems were equipped with hand brakes which activated a pulley affixed to the main shaft.

Debauve also mentions the Bernard windmill, which received the wind from behind, making it swivel automatically. The weight of the wheel was equilibrated by a cast-iron counterweight and the /4
laths on which the blades were mounted were articulated on the shafts of the blades and maintained by springs which yielded when the wind speed was too high.

In his work Die Neur Vindraeder [The New Windmills], A. Hollenberg describes the Eclipse, Excentrique, Ultra-Standard, Leffel, Bird, Champion and Halladay systems.

The English journal Engineering gave some descriptions of English wind motors in 1903, vol. 1, pages 531, 552, and 556.

In 1890 a windmill was built at the Sainte-Adresse lighthouse in Le Havre, and in America there were a large number of small electric plants powered by wind.

England had plants of this type by about 1895, and in Germany in 1904 there was one generating 220 kW of usable power.

In 1903 the Askov installation in Denmark, which Professor La Cour had been perfecting since 1891, was powering 450 incandescent lamps, 2 arc lamps and 2 electric motors. The cost price per kilowatt-hour was barely seven centimes (gold francs), or approximately 85 centimes in new francs, a cost much lower than that of public utilities.

The drawing on the May 1931 issue of the Russian journal Electrichestvo, La Technique Moderne, in its issue of November 1, 1931, notes that a wind motor installation generating 150 hp per hour under a 10-meter-per-second wind had just been put into operation in Sebastopol, in the Crimea.

The wheel of this windmill was 30 m in diameter, and rotated at 30 rpm with variations of ± 4 %, which was quite minimal.

This high regularity made it possible to connect this wind turbine to an asynchronous generator supplying 220 volts, stepped up to 6600 volts by means of a static converter to power the high-tension network of the Sebastopol docks.

Since it was mounted on well-lubricated ball bearings, the windmill was able to start in a wind of 4 m per second, even though its weight was some 4000 kg. It was installed on a steel pylon 25 m high, with a nearby plant housing the generator, the transformers, and the ordinary accessories for this type of installation.

The experiments of Coulomb (1720) in France and Smeaton (1755) in England, followed by those of Rankine, heavily contributed to the establishment of theory and practical data for the construction of modern windmills. Here is the description of Dutch and Flemish windmills given in about 1830 by Maison Rustique du XIX^e siécle /5
[The 19th Century Rustic Home]:

"Everyone knows what a windmill looks like (Fig. 2). The usual receiving device for a windmill consists of blades or vanes affixed perpendicular to the end of a horizontal shaft and uniformly distributed around it. Generally four blades are used; these are rectangular in shape and their dimensions in the vicinity of Paris are about 12 m long and about 2 m wide. In the Northern Department, the length of the blade is 38 and sometimes 13-14 m against a width of 2 m. Here is the description of the characteristic appearance of windmills in the vicinity of Lille given by Coulomb.

"1 m 67 mm of the width of the blade consists of canvas attached to a frame, with the root resting on an extremely light plank. The joint line between the plank and the canvas, on the side struck by the wind, forms an appreciably concave angle at the beginning of the blade which progressively diminishes and disappears at the tip of the blade. The piece of wood which forms the arm is located behind this concave angle. The surface of the canvas forms a curved surface composed of straight lines perpendicular to the arm of the blade and coinciding at their ends with the concave angle formed by the joint between the canvas and the plank. The rotating shaft to which the blades are attached is inclined 8-15° to the horizon."

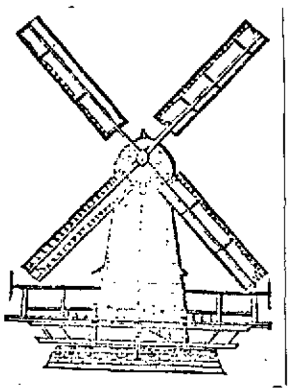

Fig. 2. Dutch windmill with rotating base.

"Vertical windmills occur in various forms. Fig. 3. shows a wooden cage with its inside framework, the entire structure rotating at will or with the wind, by means of a rudder to which a swivel and line have been adapted; this is what is termed "orienting" the windmill.

"Fig. 4 shows another windmill whose top alone rotates. Here the cage is masonry. /6

"Sometimes the windmill is constructed in such a way that it is able to orient itself; in these cases it is somewhat more complicated. Experience has shown that this procedure does not offer sufficient advantages to compensate for a structure which is more costly and more subject to repair.[1]

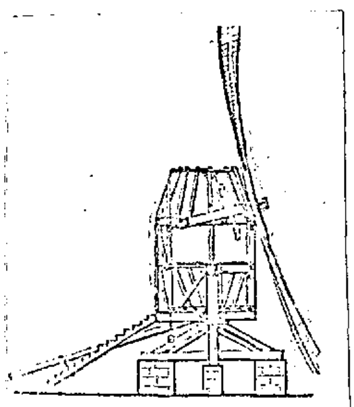

Fig. 3. Interior of an old windmill rotating on a pivot.

"The considerable irregularity and the violence of the wind frequently make it necessary to modify its force, either to regulate it or to prevent the windmill from being damaged or overturned. In this case the vanes are "stripped" to a given extent by folding back the canvases or blades. A wooden brake which drags on the inside of the wheel is used to stop the windmill.

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1 This is no longer true of the mechanisms of modern wind motors, which always have automatic orientation systems.

This operation may be performed from the outside by means of a line connected to the spring which sets this brake in motion.

"In general, when wind is used as motive power it acts on vertical vanes; although horizontal windmills have frequently been tested, they are not being used. The advantage offered by this type of windmill at first glance is the ability to turn under any wind without the necessity for orientation; however, it has the disadvantage of presenting no more than one blade at a time to the wind, while in ordinary windmills, the wind acts on all four vanes at the same time.

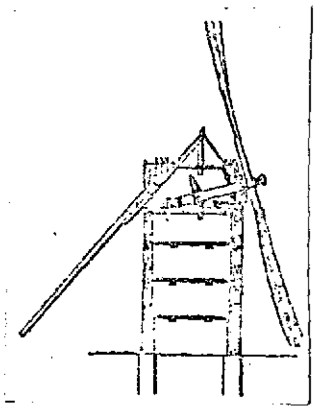

Fig. 4. Interior of an old windmill with rotating head, mounted on a masonry tower.

Fig. 5 shows the details of construction of a Dutch windmill used to drain a swamp, with a paddlewheel operating in a masonry mill-race."

In the museum of the National Conservatory of Arts and Crafts in Paris there is a collection of small-scale models and drawings of windmills and "pananemones."

These models are masterpieces of precision and workmanship; however, the models exhibited are quite old, and it is extremely unfortunate that the designers of wind motors did not consider it
apropos to offer this wonderful /7
museum small-scale models of their current inventions and designs. There is a regretable gap in this area. As a result, young engineers who come to the museum to learn are unable to find any up-to-date examples of advances in the industrial use of wind power. For the following list of exhibits I am extremely indebted to

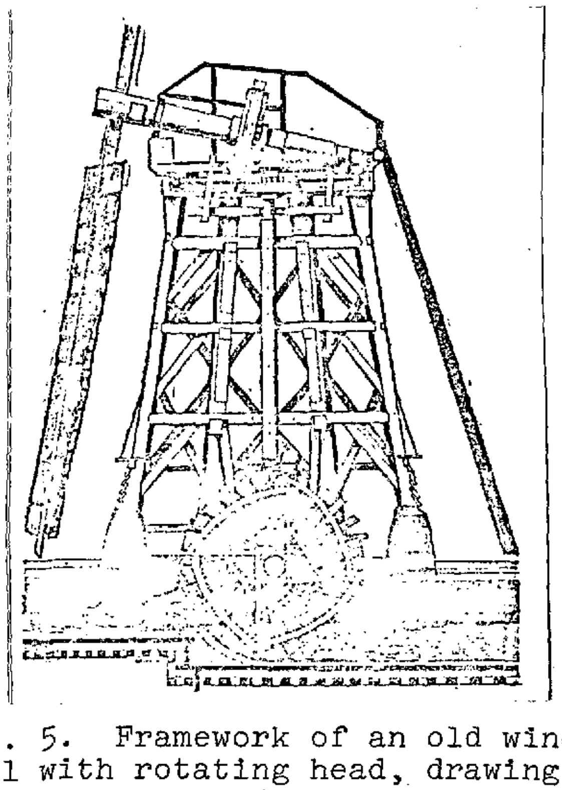

Fig. 5. Framework of an old windmill with rotating head, drawing water by means of a paddle wheel.

Mr. Landiais, curator of the museum, who was kind enough to go with me to the glass cases containing the wind motors. This is a quite valuable list, even though it is somewhat outdated, since it can still serve as a source of information to modern designers in regard to the inclination of the shaft to the horizon and that of the blade surfaces to the plane of the wheel.

It may be noted that the efficiency of the old four-blade windmills was as good as -- if not better than -- that of current wind motors, and it is therefore valuable to study these predecessors.

Here is the list of models and drawings exhibited in the National Conservatory of Arts and Crafts, 269 rue Sainte-Martin, Paris: /8

Room 24. Scale models

No. 86. Dutch windmill, rotating on rollers, powering a sawmill. 1:20 scale model executed by Bulol in 1791, after the model belonging to the Academy. (see Bulletin de la Société d'Encouragement, vol. 8, 1809, page 165.)

No. 296. Horizontal blade or vertical shaft windmill, by Clair, donated by the Institute in 1807.

No. 497. "Panemore" driving a vertical grindstone, by Clair, donated by the Institute in 1807.

No. 498. Eyme and Philippe "Panemore," Tarascon-sur-Rhône, accepted by museum prior to 1815.

No. 857. Windmill driving a pair of grindstones, masonry tower, rotating top. 1:15 model by Périer; obtained prior to 1814.

No. 1150. Windmill driving a pair of grindstones, rotating on a pivot. 1:20 model by Périer; obtained prior to 1814.

No. 2471. Windmill driving a pump; orientation by rudder; hand brake; iron frame. 1:20 model built by Philippe; obtained in 1836.

No. 2593. Dutch windmill for drawing water, 1:20 model used to drain the Zeudplatz, close to Gouba. This windmill drives an Archimedes' screw; the tower is made of wood and the head rotates. Obtained in 1840.

No. 3634. "Panemore" built by Tarbé in 1801; obtained in 1849.

No. 4074. Windmill driving four pairs of grindstones; entire structure wooden, rotating head. 1:10 model, obtained prior to 1849.

No. 5433. Windmill, 1:20 scale model, by Clair; obtained in 1853.

No. 5549. Windmill mechanism by L. Fanchot, 1:5 scale model, built and donated by the designer in 1854.

No. 7428. Windmill with regulator, Berton system. 1:10 scale model, donated by the Société d'Encouragement [Association for Encouragement...] in 1866. (see Bulletin, vol. 48, 1849, page 198.)

Note: See the description of this Berton windmill on page one previous.

No. 7553. Delamolére windmill, blades with venetian shutters controlled by a regulator; automatic orientation by butterfly valve. 1:10 scale model donated by Société d'Encouragement in 1866. (see Bulletin, vol. 24, page 186.)

No. 282 T. Automatic windmill, donated by Godrant.

Room 53. Drawings /9

No. 13571-84. Wind-driven sugar mill, Barré de Saint-Venant: one plate.

No. 13571-90. Water-air mill; one plate.

No. 13571-92. Windmill with description of figures; two plates.

No. 13571-95. Windmill mounted on a boat, dedicated to the senate of the free city of Brême by its inhabitants, one plate.

No. 13571-96. Octagonal mill with paddles, Dutch design, projected for the Grande Moëre, in Flanders; one plate.

No. 13571-233. Dutch windmill for sawing wood; two plates.

No. 13571-584. Windmill designed to orient itself automatically, in use in England; one plate.

No. 13571-1735. Self-regulating windmill, built by Fournier-Benoit, Montpellier; one plate.

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9

Chapter 2. General Considerations Regarding Wind Motors /10

Smeaton, an English engineer who lived in the middle of the 18th century, gave the following recommendations for the design of the old windmills with four blades, the number of blades which is still used today for high-powered wind motors.

"The number of blades should not be so high that the issue (i.e., escape) of the wind striking them is arrested.

"If flat blades are used, the direction of their length (i.e., of their plane) should make an angle of 72° to 75° with the rotating shaft to obtain the maximum effect.

"The wider the blades, the more they must be inclined toward the axis of the shaft.

"Blades which are wider at their tips than they are close to the center offer more advantages (i.e., have better efficiency) than those of rectangular shape.

"When the blade surface is not flat, it is to advantage to present the concave face of these blades to the wind.

"If blades of similar position and shape are presented to the same wind, the number of revolutions that they will perform in a given time is in inverse proportion to their length.

"The effect (i.e., the motive power) produced by blades of similar shape and position exposed to the same wind are proportional to the squares of the lengths of the blades.

"Blades of the same width and different lengths will produce effects proportional to their length when their inclinations are similar."

Furthermore: "Wind apparently does not follow a direction parallel to the horizon; at least it is generally recognized that blades placed in a vertical plane will not catch the wind as well as if the shafts on which the blades are mounted is inclined 8-15° toward the horizon. All constructors are in agreement on this point."

Smeaton states that the power of a windmill whose blades are /11 in a horizontal plane (these windmills are termed "pananemones") is actually only 1/8 or 1/10 that of a windmill whose blades are in a vertical plane.

We might add that these old windmills were very thoroughly tested and their efficiency was extremely high. They were built entirely of wood and were incredible feats of carpentry; the methods available at that time did not make it possible to build them out of iron or steel.

Thus according to Smeaton a windmill will yield maximum efficiency when its blades are left-hand surfaces whose generatrices, located at the points obtained by dividing the length of the blade into six equal parts, form the angle given in the following table with the axis of the wheel or the direction of the wind. In this table, generatrix number one is that located at the point of division closest to the axis; it is at this point that the blade, or useful area of the vane, begins.

Numbers of generatrices	Angles formed with axis	Angles formed with the plane of movement of the vane
1	72°	18°
2	71°	19°
3 (center of vane)	72°	18°
4	74°	16°
5	77.5°	12.5°
6	83°	7°

A difference of a few degrees from the values given in this table does not seem to have much influence on the efficiency of the assembly.

The width of the vane is between 1/5 and 1/6 of its length, and should never exceed 1/4.

The vane may have the shape of a trapezium whose side, at the tip of the vane, is 1/3 the length of the vane; the small side, next to the shaft, is thus equal to 1/6 the length of the vane.

The speed of the vanes at their tip should be 2.5-2.7 that of the wind for the windmill to operate at optimum efficiency, when the vanes are well oriented and when they are rotating without any load.

Smeaton concludes that the loads are roughly proportional /12
to the square of the wind speed; thus if the speed is increased from one to two, the load will have increased from one to 3.75.

As a result, the effects produced are roughly proportional to the third power of the wind speed. This was confirmed experimentally by Smeaton, who found that with speeds changing from one to two, the effects produced increased from one to 7.02.

The efficiency in kilogram-meters per second is equal to KSV^3, with coefficient K equal to 0.05 according to Smeaton and 0.03 according to the experiments performed by Coulomb on a large windmill in the vicinity of Lille; S is in square meters and V in meters per second.

The equation for the efficiency of a windmill is the same as that of a suspended wheel in a watercourse. The only difference is in the value of the numerical coefficients.

According to J. Claudel, the pressure exerted by the wind against a flat surface perpendicular to its line of movement is as follows for speeds of less than 10 m/sec:

$$P = 0.11\ d\ S^{1,1}\ V^2;$$

or roughly:

$$P = dS \times 2\ h$$

P being the pressure in kilograms per square meter;
d being the weight of a cubic meter of air (approximately 1.293 kg);
V the wind speed;
$h = V^2/2g$, the height of origin of the speed ($g = 9.81$ on the seacoast);
S the area of the plane in square meters.

The first equation shows that P increases in a higher proportion than the area struck by the wind.

According to Borda, three plates whose surface areas were proportionate to the series 1, 2.25 and 5.06 yielded expressions proportionate to the series 1, 2.44 and 5.97, values whose rate of increase is roughly the same as the 1.1 powers of the surface areas.

According to Hutton, when the wind strikes a surface at a given angle, the pressure which it exerts on the surface is:

i being the angle of the surface with the direction of the wind. /13
If i is a right angle, $\cos i = 0$ and $\sin i = 1$, and as a result $(\sin i)^{1.84 \cos i} = 1$, and Eq. (2) becomes Eq. (1) above, which is normal.

The dimensions of the old four-vane windmills were as follows:

squaring of the oak shaft: 0.50 m to 0.60 m
inclination of shaft to horizon: 10-15°
length of vanes measured from shafts: 10-12 m
squaring of shaft of vanes close to the main shafts: 0.30 m
spacing of bars supporting canvas: 0.40 m
usual area of each vane: 20 square meters.
(after J. Claudel.)

Note on the computation of wind motor efficiency. An ideal wind motor would be one capable of using all the kinetic energy of the wind.

None of the assemblies designed so far have been able to obtain this result. The wind reaches the blades on the wheel at a speed V, passes through the plane of the wheel and still retains a speed v which is estimated to be equal to V/3.

Thus the wind has supplied only 2/3 of its kinetic energy to the wheel, and since it appears impossible to obtain better results, some designers compute the efficiency of their wind motors on the basis of 2V/3 rather than V, which increases the apparent efficiency of the wheel by 1/3.

The exactness of this method of computation is arguable, since the available energy is actually the kinetic force of the wind at a speed V, and a better assembly would be able to use all this energy, or at least most of it, rather than merely 2/3.

Uses of windmills. Windmills are used primarily to draw water, to drain swamps and for irrigation. There are a number of large installations in Denmark, Holland, and the colonies; some agriculturists in Tunisia use them to draw up to 1,000 liters of water per hour to heights of 25 m, to cultivate orange trees; and thousands of wind motors are in use in Algeria, Tunisia and Morocco to draw water.

They are also used to generate electricity, by means of compound generators with suitable circuit-breakers. /14

Experiments performed in Algeria by Commander Riet have shown that a wind motor is usable for 70% of the year and a wind wheel with a radius of 5 m will monopolize a horizontal area equal to a circle with a radius of 60 m. Thus by a judicious distribution of wind motors it would be possible to obtain 7800 hp per hectare per year. (51st Conference of the French Association for the Advancement of Science, Constantine, April 13-25, 1927.)

To correct the irregularity of the activity of windmills or wind motors, these assemblies have been intended for use only in drawing water continuously into a large-capacity tank elevated as high as possible, 20 m or more above the ground. The water stored in this way at no cost is then used to activate a hydraulic turbine which controls the dynamo.[2]

The installation costs for this assembly are fairly high, but it does make it possible to use all the power of the wind, to keep this power in reserve, and to use it only when needed, without waste. The tank turbine is supplied with water through a simple pipe from a raised tank; its mechanical efficiency is excellent.

The generator, which can be activated instantaneously simply by maneuvering the watergate of the turbine, is able to supply current directly to the user equipment. This eliminates the use of a storage battery, which is costly, requires maintenance, and yields poor efficiency; this battery is actually replaced by a water tank which is a true power accumulator of the best possible type. The water is then used for irrigation and other purposes, and it can also be returned from the well from which it has been drawn after it has yielded up its energy in the hydraulic turbine.

This process is therefore extremely practical and advantageous.

From the standpoint of computations for an installation of this type, according to Plissonnier, a Lyon constructor, a wind motor or air turbine is able to raise the following quantities of water to a height of 8 m under a wind of 10 m per second: /15

Diameter of air turbine	Liters water raised to an 8-meter height per hour	Accumulated power in horsepower per hour
5 meters	20,000	0.59
6 meters	32,000	1.19
7 meters	49,000	1.45
8 meters	58,000	1.71
9 meters	66,000	1.95
10 meters	76,000	2.25

[2] The journal la Nature, in its issue for the second half of 1884, page 286, mentions the installation set up in America under the name "Arastras," consisting of a sort of dredger which lifts sand into a reservoir from which it is dropped onto a bucket-wheel or a chain-pump. This is a sand accumulator which appears to have yielded good results, although its efficiency does not seem to have been very high; however, the motive power does not cost anything.

One might arrange to use the water turbine only a few hours a day, with the result that a windmill 10 m in diameter struck by a 10 m per second wind for only 10 hours per day would accumulate 22-1/2 hp per day, making it possible to activate a 4 hp hydraulic turbine for 5 1/2 hours, and as a result, an extremely powerful generator which could be used for practical purposes. However, in this case the water tank should have a capacity of 6-7 m^3 to make up an adequate reserve.

In regard to previous uses of wind generators to produce electricity, we may mention the following information given in an article by Ch. Groud, engineer, published by the Electrojournal.

On broad plains or plateaus with no waterways of any size, wind is virtually the only natural source of motive power.

Wind has been used for a very long time, perhaps even more in the past than at present. This is because wind is extremely unstable, extremely irregular, and frequently nonexistent. Waterfalls are much more convenient to use and are also more constant. Consequently, attempts are made to make use of waterfalls before considering the use of wind, but nevertheless there is bound to be widespread use of wind power in the future.

Variations in the speed of wind are of broad amplitude and occur very quickly. Here automatic regulation of the assembly is extremely important. When the wind exceeds a given speed (storms), the wind generator should fold up or close; in this case it is said to elude the storm.

Windmill theory is still imprecise. Considering only the pressure on an immovable flat surface perpendicular to the direction of the wind, this pressure is given by the equation: /16

$$F = 0.125V^2 \times S$$

S is the area in square meters;
V is the speed in meters;
The result F is expressed in kilograms.

Given these conditions, a 40 m/sec wind (hurricane) would yield a pressure of 200 kg per m^2. With the wind of 10 m/sec wind (brisk wind) the pressure would be more than 12.500 Kg/m^2.

It can therefore be seen that if the wind speed varies a great deal, the pressure produced will vary still more, since it is a function of the square of the speed. Moreover, most wind does not supply very high pressure per square meter. To obtain significant power, therefore, it must be confronted with a considerable surface area.

The above equation is relatively simple, but it becomes somewhat more complex when the surface is concave, convex, or turned up at the ends. Furthermore, in the case of a windmill vane moving under the effect of the wind, consideration must now be given to the relative speed of the wind in comparison to the vane.

Coulomb established the following formula to obtain the work which could be supplied by a windmill:

$$T = nSV^3$$

n is a coefficient which Coulomb has given as 0.03, but which actually can vary tremendously; S is the movable surface area and V is the wind speed.[3]

The term V^3 is exact in practice only when the load is increased as the wind speed increases, with this increase in load being proportional to V^3. /17

If this method is not used, as the wind speed increases, the speed of the vanes also increases and the usable mechanical work is proportional to the wind speed rather than the third power of the wind speed.[4]

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3 According to Professor Ringelmann, the values of the coefficient n are as follows:

Wind speed in meters per second	Values of n
4.10	0.0198
4.65	0.0156
5.26	0.0115
6.60	0.0081
7.50	0.0063
8.90	0.0039
10	0.0030

4 Taking into account the suction produced by the wheel behind the vanes, Professor La Cour gives the following formula for the work produced by a four-vane windmill:

$$T = \frac{SV}{1250}$$

in which the output is assumed to be proportional to the speed of the wind and not to the third power of the speed.

The use of windmills to generate electrical power has already given rise to a few interesting applications, especially in Denmark.

For example, in Askov in 1891 there was one wind motor with four vanes, 6 m long by 2 m wide, and another with four vanes 7.40 m long by 2.50 m wide. The first was used to electrolyze water for the production of oxygen and hydrogen. The second wind motor powered two 9 kW generators. One of these generators produced oxygen and hydrogen, as previously, and the other charged a storage battery and powered a power and light network.

The test which led to the realization of this plant first showed that it was advantageous to place the shaft of the generator high above the ground, and second that the four-vane generator, with its economical and convenient design, had the best efficiency; however, the disc wind generator started more easily under low winds. With fewer than four vanes, the proportion of available power used decreased; with more than four, on the other hand, there were reactions and eddies between the vanes and the efficiency was low. In addition, it was advantageous to reduce the area confronting the wind to a minimum.

The peripheral speed of the vanes, V X 2.5 (V = wind speed) is that permitting maximum efficiency. The angle between the surface of the vane and the direction of movement should be 10° at the tip and 25° at the center. The wind should be prevented from striking the vane with a heavy impact.

In this specific case, the Coulomb equation becomes, in kilogram-meters:

$$T = 0.06\ SV^3$$

If P is the power expressed in kilowatt hours, one obtains the formula: /18

$$P = \frac{SV^3}{1695}$$

Denmark is a country in which the wind blows fairly continuously, and in which wind motors are advantageous as a result. Thus installations similar to the above have multiplied. A wind generator built on the island of Zealand has a blade area of more than 30 m^2. Under a 7 m per second wind it is able to furnish 8 hp at an angular speed of 24 rpm.

In 1897 Professor La Cour supervised the installation of a wind motor in Askov whose blades were 11.40 m long and which was used for tests and experiments.

In these various installations, energy was transmitted from the control shaft of the wind motor to the generator by pulleys and belts. These were held by a movable rig with counterweights which made it possible to adjust the tension and limit the adherence of the generator on the pulley. Under these conditions, an increase in speed of the wind motor shaft merely slides the belt over the pulley and the transmitted torque remains virtually constant.

The speed of the generator is adjusted automatically according to the charge state of the battery, and the intensity is automatically regulated according to the charge. The speed of the generator varies with the voltage required.

If the wind happens to slow down, the speed of the generator may become inadequate to obtain a voltage higher than that of the battery. In this case the battery discharges into the generator, which, rotating in the same direction, acts as a motor and accelerates the rotation of the vanes. This drawback is avoided by means of an automatic relay. The generator and the accumulators are connected only when the generator voltage is higher, and they are disconnected in the opposite case.

In this procedure, the generator is directly connected to the storage battery, whose capacity should be carefully studied. A study of meteorological observations will show the approximate frequency of the wind and its intensity.

Another system, also used in Denmark, is capable of tolerating wide voltage variations. The generator is directly connected to the power circuit, with the batteries on a branch circuit serving /19
as buffers. In the lighting circuit, the voltage is kept constant by an automatic end cell switch which places a given number of cell-boxes in the circuit, depending on whether the batteries themselves are charging or discharging in the power network. The maximum speed of the generator corresponds to the maximum speed of the wind motor.

In this case, the generator may be driven by gears affixed to the shafts of the wind wheel, as we will see in regard to the Danish Aurora wind motors.

At this maximum speed, the generator supplies a voltage which should still be accepted by the batteries; they will reject the current when they are completely charged.

This system uses some devices from the preceding one, notably the relays. Its efficiency is better. The assembly has an additional winding connected in series to the small motor of the automatic end cell switch, and thus excitation is always ensured.

The Zealand installation which was mentioned above supplies power for 378 incandescent lamps, 6 arc lamps, and one 4 1/2 hp engine, activating a kneading machine and a band-saw. This installation, which was built long before the war, cost 19,000 francs, including the building. The storage battery alone, which consists of 6600 ampere-hour cell-boxes, cost 5500 francs. The installation has an emergency 10 hp gasoline engine, which operated for only 90 hours in 1904. The annual costs, including interest and amortization, were estimated at 3000 francs, or 0.40 francs per kilowatt hour for the entire year. This cost was not so high for the winter alone, the period of highest consumption.

In his valuable experiments on modern wind motors at the Askov testing station in Denmark from 1891 to 1900, Professor Le Cour arrived at the following conclusions:

1. All else being equal, the pressure of the wind is proportional to the area of vanes of similar shape; it is also proportional to the square of the wind speed.

2. The useful work of a flat vane does not equal half the useful work of a concave vane.

This second rule contradicts the opinion that the pressure of the wind acts on the vanes at right angles, and Professor Le Cour found that a 1 m/sec wind striking a flat vane will yield 42 gram-meters of work/m^2 of surface area, the speed of the vane being 2.2 to 3 times that of the wind and the angle of the plane of the vane 12.5°. With a vane with a broken surface the maximum work /20
obtained is 108 gram-meters, the speed of the vane being three times that of the wind, at an angle of 7.5°.

The resistant surfaces of the vanes on a wheel should be minimal and should cover no more than 1/6 of the circular periphery. The motive power is thus approximately 77 gram-meters, and the inside parts of the vane can take up a larger part of the periphery without loss of power.

Professor Le Cour recommends the use of only four vanes whose width is equal to 1/4 or 1/5 their length and is constant over the entire length. The surface of these vanes should begin at a distance from the shaft equal to the width of the vane. The cross section of the vane will be a curved or broken line, one part of which will be three times greater than the other, moving forward; the distance between the chord of the arc and the peak of the angle will be 3-4° of the width of the vane; a continuous transition (that is, a connection in the form of a flattened and continuous curve), as indicated by the dotted line in Fig. 6, will be provided between the two portions of the vane; a straight line drawn from the forward edge to the rear edge at the tip of the vane will make an angle of 10° with the plane of the wheel (direction of movement of vane), and this angle will increase as the vane approaches the center, where it will be 25°. The vane is thus warped in helicoidal form. The speed of the vane at the circumferance of the wheel will be 2.43 times that of the wind.

Given the above conditions, the useful work of the wheel will be 60 gram-meters/m^2 of area of the vanes under a 1 m/sec wind and will increase in proportion to the third power of the wind speed.

To obtain a uniform speed for the wheel, Professor La Cour recommends the use of vanes automatically turning aside under the thrust of the wind, their angle of opening varying with the speed. He estimates the efficiency of a suitably designed windmill at 21 %.

The above characteristics are shown in the following figures:

Figure 6: Cross section of a vane of width mn; the maximum deflection F = 0.04 mn; the dotted line indicates the continuous curved profile of the vane.

Figure 7. Diagram of a wheel with four vanes; the vanes are of equal width at 1/4 of 1/6 of the circumferance of the wheel, that is, $\frac{1.04^{2}\ R}{4}$, 1.042 being the length of the arc subtended by /21
a chord equal to one; the vanes have an inclination of 25° at the center and 10° at the circumferance; the distance ab from the center of the wheel to the vane is equal to the width of the vane.[5]

According to Debeauve, the vane should begin at a distance from the center equal to 1/4 the radius, and its width should be 1/6 the radius of the wheel, with its inclination being the same as the angles given by Smeaton above. The work furnished by a vane of this type may be computed by the formula $T = 0.12\ SV^3$, S being the surface area of the vane and V the speed of the wind.

---

[5] In the four-vane windmills used in Holland, the angle made by the end of the plane of the vane with the plane of the wheel is zero, or in other words, the tip of the vane falls within the plane of the wheel. The designers of these windmills have the last crossbeams of the vanes turned back, even slightly, in an opposite direction to the direction of movement, since they have found by long experience that this will improve efficiency.

Monteil states that long experience has shown the validity of this practice, which probably originated in the effects which could be expected from the bending of the crossbeams supporting the canvas, and which would combine with the torsion of the shaft of the vane to re-establish an inclination when the wind acts on the vane (Boulvin, 41-297).

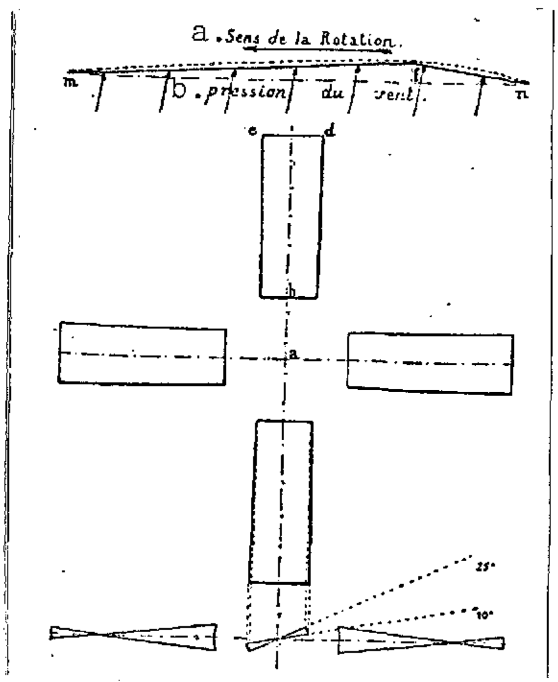

Fig. 6 and 7. Section of a vane and diagram of a four-blade wheel.

Key: a. direction of rotation
b. wind pressure.

A satisfactory wind motor is able to start in a 2.50 m/sec wind, although some assemblies require wind of 3.50-4 m/sec.

A wind with a speed of 2.50 m/sec is virtually imperceptible; wind at this speed is common and of daily occurrence, as shown by the observations made over five consecutive years by the Official Observatory of Saint-Maur Park which are given in the table on page 121. (265)

Thus the wind motor will operate for an average of 450 hours out of a total of 720 per month, that is, 15 hours a day out of 24. Every farm and ranch in America has a windmill, sometimes two or three or even several dozen. However, it would surprise a good many Frenchmen to learn that the wind system in France is at least as favorable as in America. It is quite easy to make a partial check of the wind system in a given region by means of the table given on page 121.

Hütte's German Engineering Manual thus gives a method of computation for wind motors:

The wind motor should start easily enough so that its work will begin when the wind speed is 2 m/sec, to drive pumps; to drive generators, the work should begin under a 3 m/sec wind.

The work furnished by the wind can be stored in storage batteries or in water tanks of a given elevation which subsequently are used to drive a water turbine.

The available energy of a wind wheel is approximately equal to the momentum of the steel weight reached by the blades during 1 sec.

$$P = \frac{dSV^3}{150g}$$

in which d is the weight of a cubic meter of air at 50° C and 760 mm of mercury or one atmosphere; d = 1.186 kg/m^3 air.

S is the projection of the total area of the blades, in square meters.
V is the wind speed per second.
g = 9.81, the acceleration of gravity.

The useful power of a wind wheel depends on:

1. The distribution of the vanes on the wheel; between the vanes there should be an adequate cross-section to allow the free passage of air. /23
2. The curvature and the angle of attack of the vanes.
3. The design and maintenance of the moving parts.

The above equation does not take into account:

1. The influence of the static pressure of the air due to the suction effect of the wind on the rear side of the vanes.
2. Losses due to vorticity.
3. Losses due to the momentum of the wind upon leaving the wheel.

The mechanical efficiency of the wheel alone ranges from 0.6 to 0.9.

Note. The losses due to the three causes listed above are so significant that some investigators have considered the output of a wind motor to be proportional only to the square of the wind speed, or even the wind speed itself (Professor La Cour).

In his Cours de Mécanique [Course in Mechanics], 3rd edition, volume 2, Boulvin notes that M. A. Rateau, a member of the Academy of Sciences, recently deceased, considers American wind turbines with curved vanes to operate by reaction and assumes that this observation may be applied to wheels consisting of a large number of flat plates, like those of the Halliday windmills.

From the expansion of this theory, Rateau concludes that the peripheral speed at the tips of the vanes should be 1.2 V in normal operation.

V being the wind speed, the retardation of the wind as it approaches the wheel is 17.4 %, furnishing a value of 0.32 for the degree of the reaction and a value close to 45° for the angle of entrance of the wind.

Monteil, who published the third edition of Vol. II of Boulvin's work, states that Murphy estimates the efficiency of the wind motor (which will be described in this volume) at 0.26, which would give it an output in horsepower of 0.0002 SV^3. Algebraic computations confirming these results may be found in Vol. II of the third edition on pages 269-270.

In general, the output of a wind motor is given by the formula:

$$T = \lambda SV^3$$

in which S is the total area of the vanes, V the wind speed and λ a coefficient which Smeaton estimates as 0.05 and Coulomb and Navier as 0.03, for the vanes of Dutch windmills. /24

The horsepower rating per 75 kg would thus be between 0.0006 and 0.0004 SV^3.

One can see the wide difference in estimates from one investigator to the next, and it is for this reason that we are furnishing a number of designers' reports in this volume in order to make the discussion as concrete as possible.

Vanes

Wind motor wheels have been built with vanes consisting of small thin wooden planks (ash, fir, or beech), set at angles like those of the shutters of venetian blinds (Halladay, Vidal Beaume, Figs. 19 and 32), but today they are more often made of steel plates, which can be given the optimum theoretical curviture for the use of wind.

The Adler, Aurora and Agricco windmills have four to eight vanes which are shaped somewhat like a fish in cross section, as shown by Fig. 41. The profile of these thick vanes is that which is currently recognized as optimum for aircraft wings: the wind attacks the vane on its thick rounded edge, thus yielding optimum efficiency. These vanes are able to pivot on shafts following the radii of the wheel so that they can be turned aside during excessive winds, or they may be fixed in position, with deflection of the wind by lateral ailerons.

Constantin and Darrieus, whose respective work will be discussed later on, also recommend the use of thick vanes.

As shown by the large number of tests performed, and according to the opinions given above, it is not advantageous to increase the number of vanes indefinitely. A wheel with four or five well-designed vanes will be more efficient than a wheel with a number of overlapping paddles. In addition, a similar observation has been made with regard to aircraft and ship propellers with more than four blades: a large number of blades will form a sort of plane which will obstruct the passage of the wind, while four blades will catch the wind and the air current will pass through them, acting on their entire surface area. Consequently the large Danish wind motors have only four or five vanes.

Wind wheels currently can be divided into two distinct classes:

1. Those with a small number of blades (2-6) turning at high speeds (Danish and German designs, the Constantin and Darrieus wind motors), whose efficiency is the highest.

2. Those with blades over the entire area of the wheel, whose speed is 1/4 or 1/5 of the preceding (French and American design). /25

The latter are able to start under a 2.50 m/sec wind, while the former require a wind of at least 4 m/sec.

The high rotation speeds cause vibrations in the moving parts and pylons which can be avoided only by rigorous static and dynamic equilibration of the wheel.

Wind motors with a large number of blades, which are known as American wind motors, although they were first developed in France, thus seem to be ideal for the supply of small quantities of motive power in countries where most of the wind is low speed.

On the other hand, the wind motors with two, three or four blades mentioned above are preferable for heavy electrical production in regions selected for their exposure to high-speed winds.

In this connection we hope the reader will examine the illuminating reports which Mssrs. Constantin, Darrieus, and Lacroix have been kind enough to furnish for this volume.

Orientation of Wheel

To use extremely low-speed wind, the wheel should be positioned perpendicular to the wind. This automatic orientation may be obtained either by a rudder kept perpendicular to the plane of the wheel, or by a small single or double auxilliary turbine known as a wind rose (Fig. 25), whose plane is perpendicular to the plane of the main wheel. If the wind blows crosswise, the wind rose turns in one direction or the other and pivots the plane of the main wheel by means of gears which it generally drives by means of a perpetual screw; the horizontal main shaft of the wheel is thus installed on a vertical-axis stem or platform.

The rudder system, which is quite simple, is used for small windmills, and the wind rose system for large wind motors, since it has the advantage of operating more gradually and producing less violent jerks than the rudder.

We will see examples of these two systems in the assemblies described later on; figures 19, 21, 33, etc. give examples of orientation by rudders, while figures 38, 44, 46, etc., show orientation by wind roses.

Another procedure consists in positioning a winddwheel with small vanes or helicoidal blades on its shaft in such a way that it faces away from the wind. In this case the vanes receive their /26 thrust from behind and the wheel will always tend to pivot in the direction of the wind. This design for orientation is primarily used with wheels having two to four blades, where there is no danger of violent winds. (See Figs. 128 and 178.) In this way the orientation and blade deflection mechanisms are eliminated.

Deflection of Vanes or Wheel

It is to advantage to keep the speed of the wheel as constant as possible, or at least to limit it to a well-defined maximum. Moreover, in the case of a hurricane it is absolutely necessary that only an extremely reduced area be presented to the wind; and finally, when the assembly is not in use it should be possible to remove the wheel from the thrust of the wind and stop it.

Two different methods are used to obtain this result.

(1) Deflection of Vane Elements

The vanes are composed of one or several elements able to pivot on a shaft. Since this shaft is not at the center of the superficies of the vane element, this element will tend to tilt constantly in the wind. However, opposing counterweights or springs are used to bring the element into a position perpendicular to the wind, and when the wind exceeds a given maximum speed, the vane element tilts and allows the wind to by-pass it in proportion to its excess speed.

Fig. 8 shows a Halladay wheel element (American). The vanes pivot on the rigid shaft ab, which is supported by the spokes ac and ab on the hub and assumes the position shown in Fig. 9 during high winds. The drawback springs or counterweights are not shown in this diagram.

Fig. 10 shows the vane elements of the Reinsch wheel (Germany), /27 which pivots on shafts along the spokes of the wheel; these shafts are not in the center of the vanes, with the result that the wind tends to pivot them.

In Fig. 47, showing the Mammouth windtturbine (Denmark), the vanes consist of elements pivoting on shafts perpendicular to the arms or spokes of the wheel. Fig. 48 shows these elements turned aside in hurricane winds; the shafts, in the lower lefthand corner of the photograph, indicate the violence of the wind at the time the picture was taken. The deflection of the vane elements is

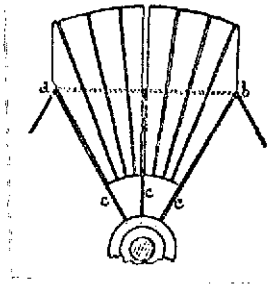

Fig. 8.
Halladay
vane in
the wind.

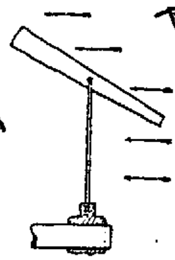

Fig. 9.
Halladay
vane turned
aside.

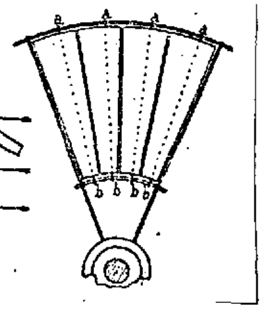

Fig. 10.
Reinsch
vane.

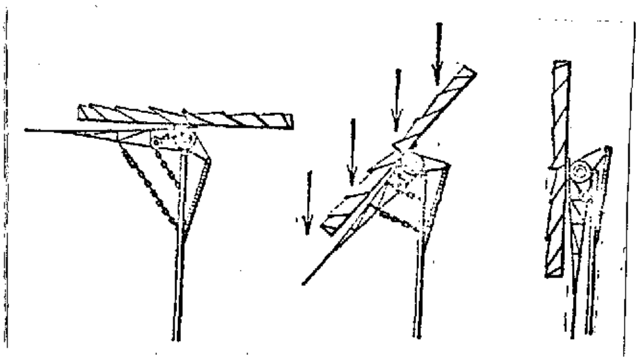

Fig. 11. Adjustment by aileron.

controlled by an auxiliary wheel termed a "wind rose" (Fig. 50).

In all these systems the wheel is rigidly connected to the rudder, which is always perpendicular to it. Some designers connect the movable elements to a group of small rods which may be activated by hand from the base of the pylon to stop the wheel.

(2) Deflection of Entire Wheel

In other cases, the arm on which the rudder is mounted is joined to the mounting of the shaft of the wind wheel, with the result that the rudder is able to fold back against the plane of the wheel, and the assembly thus automatically turns in the direction of the wind, to which it offers only minimum resistance. A mechanism of some sort, a rod or chain, makes it possible to fold the rudder back against the wheel from the base of the pylon to bring the wheel to a halt (Figs. 27 to 30).

The rudder G is joined to a vertical mounting, and the wheel (Fig. 19) is rigidly connected to a blade or aileron p which always remains parallel to it. When the wind speed increases, it pivots the mounting of the wheel, whose plane approaches the plane of the rudder; a counterweight C tends to bring the wheel into a plane /28 perpendicular to this rudder. Fig. 20 shows the wheel and its blades parallel to the rudder G.

Fig. 11 shows the positions of the wheel, with its aileron and rudder, relative to the force of the wind.

(3) Deflection of Wheel by the Use of an Excentric Wheel Mounting

The vertical plane containing the main shaft of the wheel is parallel to and at a slight distance from the plane of the shaft or rod which transmits power from the wheel to the ground. The tail or rudder is attached to the pivoting head of the wind motor, within the plane of the axis of the pylon. As a result, as shown in Fig. 12, the thrust of the wind on the plane of the wheel tends to align the wheel in parallel with the rudder, that is, to remove it from the action of the wind.

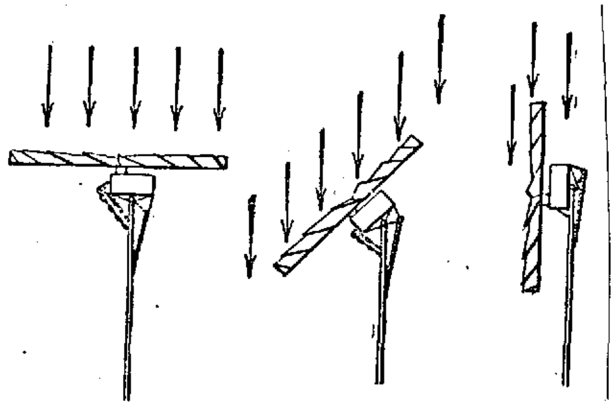

Fig. 12. Adjustment by offsetting of wheel. 1. The pressure of the wind on the offset part of the wheel is less than the force of the spring. 2. The wind pressure is slightly higher and the assembly adjusts. 3. The wind pressure is powerful enough to halt the assembly.

An appropriately designed long and powerful spiral spring tends, on the other hand, to bring the rudder into a position perpendicular to the plane of the wheel, on which the wind is thus able to act.

Fig. 12 shows three positions assumed by the wheel and the rudder, respectively, in normal winds, strong winds and extremely high winds.

Conditions of adjustment. A satisfactory windmill should adjust under an airflow corresponding to a wind speed of 7 m/sec. The wheel should begin to furl parallel to the direction of the wind when the speed imparted to it by the wind becomes excessive. /29 (wind in excess of 10 to 12 m/sec). The wheel should be completely furled when the wind speed reaches storm levels.

Use of Centrifugal Force

Consideration has been given to various devices involving a ball governor acting by means of rods which control the wheel or the vane elements. The inventor of this system, Bernard, is mentioned by Debeauve in Le Manuel de l'Ingénieur. This complicated system does not appear to be superior to the simple procedures described above. Debeauve mentions a number of types of windmills used around 1872.

The A. Dumont Wind Turbine

This assembly consists of a large sheet metal cylinder into which helicoidal surfaces have been riveted. The assembly is oriented by means of a rudder; the shaft of the turbine is horizontal and the pivoting shaft is vertical.

Bollée Turbine

This assembly consists of two paddlewheels, one of which is fixed and serves to direct the wind, while the other is movable and furnishes the drive power. The weight of the assembly is more than twice that of an ordinary wheel and the efficiency is no higher. Orientation is obtained by means of a small auxiliary turbine (wind rose).

Sanderson Airscrew

Helicoidal surfaces attached to a horizontal shaft; poor efficiency.

Polish Windmill

A ring with guide vanes transmits the wind to a paddlewheel.

Greek or Anatolian Windmill

A given number of hemispherical vanes rather like scoops or spoons are mounted on a wheel. This is a type of horizontal-blade wind motor ["pananemone"] (see Chapter 7).

Summary of the Conditions for Construction and Installation of Wind Wheels

The power obtained depends on: (1) the distribution of vanes on the wheel; between the vanes there should be openings of an adequate cross section to permit the free flow of the wind; (2) the curvature and angle of attack of the vanes; and (3) the inclination of the shaft of the wheel from the horizontal; since wind generally blows from low to high elevations, it is a good idea to place this shaft at an angle of approximately 14° with the horizon. One should take into account: (1) the arrangement and construction of the moving parts and ease of lubrication and /30 maintenance; (2) the effect of the static pressure of the air due to the suction produced by the wind behind the vanes; and (3) losses due to vorticity and the momentum of the wind upon leaving the vanes.

The mechanical efficiency of the wheel will be only 0.6 to 0.9% of the power transmitted by the wind.

The assembly should be constructed of high-strength steel, protected against rust by galvanization, parkerization or painting. Its inertia should be low and it should be mounted on ball bearings or rollers. Lubrication should be required once a year, and the pylon should be elevated at least 3 m above surrounding obstacles, which should be at least 150 m away.

Transmission Components

When the purpose of the assembly is merely to draw water, a special-model suction and force-pump or, in the case of deep well, a priming pump, is placed at the foot of the pylon. These are single-action pumps. A disk-crank is mounted on the shaft of the wind wheel and the energy is transmitted through a long rod made of wood or steel tubes, which operates only in traction to preclude buckling due to its extensive length.

Because of the high rotation speed of the wind wheel, some designers place a reduction gear between the shaft of this wheel and the crankshaft which activates the transmission rod to the pump. Figs. 22 and 23 show the mechanism of this type used by the Aermotor Co. Here the pinion g is affixed to the shaft of the wheel and drives a double gear d (1:3 ratio) on which are mounted two crank-pins which drive two rods c which attack the rod of the pump a guided into b. This pump rod thus moves in a straight line and can be guided from high to low by means of rollers or slides. This reduction eliminates dead centers and facilitates the starting of the wheel, which can be set in operation by 2 to 3 m/sec winds. The shafts of the gears with crank-pins are cut away from the pump rod, with the result that they operate more efficiently during the ascent of this rod than during its descent. The entire gear runs in an oil bath in a gear-box e.

Rotary transmission wind motors have a shaft from the top to the bottom of the pylon, guided by intermediate journal boxes, placed in rotation by a gear attached to the shaft of the wind wheel. Figs. 28 and 30 show mechanisms designed to receive and convert the movement of this shaft at the base of the pylon; /31
chain and belt transmission systems have been used with little success, in view of the considerable height of the pylon and the vertical direction of transmission.

Lubrication

Access to the journal boxes and gears at the top of the pylon is difficult, and the designer should provide these units with oil baths whose supply of oil is large enough that it will not need to be replenished very often. Some wind motors need lubrication only once a year.

Pylons

Wooden pylons have been constructed, but it is preferable to construct the pylon of steel angle irons anchored in a reinforced or non-reinforced conrete block embedded fairly deeply in the ground. Three-legged pylons are built for small wind motors, but it is better to use four legs, furnishing a square base equal to 1/5 the height of the pylon on a side.

In some cases the pylon is mounted on a masonry or reinforced conrete tower and the water tank is placed inside this tower, with a central stack containing the transmission rod or shaft (see Chapter 9).

As far as possible, the wind motor should be located on a hill-top or knoll, and its pylon should raise it at least 3 to 4 m above trees, buildings, rocks and other obstacles located within a radius of approximately 150 m, to preclude eddies and to allow the wind to pass freely.

Galvanization

The vanes, the various moving parts and the steel pylon should be carefully galvanized to withstand atmospheric attack.

Any wooden parts should be coated with carbonyl or carbonyleum once a year.

Speed of the Wind Wheel

From the standpoint of efficiency, it is better to use a small-diameter wheel rotating at high speeds, 100 rpm or more, than to use a large wheel rotating more slowly.

Theory of F. Verdeaux. In a highly informative article published in the Revue générale des sciences pures et appliquées [General Review of the Abstract and Applied Sciences] of October, 15, 1927, F. Verdeaux, Engineer of Skills and Manufacturing, describes the conditions for the operation of wind wheels. He has been kind enough to allow us to reproduce this article, which provides useful and enlightening information on this complex problem, in its entirety. Its text follows. /32

Operation of Wind Wheels

"I. Definitions. Here we will assume the wind wheel to have a horizontal shaft, as is generally the case. It consists of a given number of vanes or blades arranged along the radii and consisting of portions of surfaces which we will initially consider helicoidal.

Since the main problem involved in constructing and particularly in installing these assemblies on pylons is their large size, one basic assumption is that the purpose of rational design should be to obtain maximum power with the smallest possible external diameter.

Theoretical elemental efficiency at distance r. Let us consider two cylinders having the same axis as the wheel and radii r and r + dr. Their area of intersection with each vane is an elemental helicoidal surface of width dr, with its length being equal to the width of the vane, and whose inclination from the axis will vary.

The theoretical elemental efficiency is the ratio of the mechanical power produced by the surface element ds, as it has just been defined, to the kinetic energy of the air current striking this element. In this discussion the air current will always be assumed horizontal.

If dP_0 is the tangential thrust on ds, u the peripheral speed in m/sec, V the wind speed in m/sec and ϖ the weight of a cubic meter of air in kilograms, the kinetic energy of the wind in kg/m/sec will be:

$$dW_0 = \frac{\bar{\omega}}{2g} V^3 \sin \alpha ds$$

and the efficiency at a distance r from the axis, setting aside any energy losses, will be:

$$\rho_r = \frac{dP_0 u}{dW}$$

α being the inclination of the helix element to the axis, or the incidence of the wind.

Mean efficiency ρ_m. This is defined by the equality:

$$\rho_m S = \int_{ri}^{R} \rho_r dS$$

S being the total area of projection of the vanes onto the plane of the wheel, r_i being the minimum radius at which the vanes begin, and R being the external radius. /33

Since knowledge of the mean efficiency is a basic requirement for any design, the power collected under a wind speed V is:

$$W = \frac{\bar{\omega}}{2g} V^3 S \rho_m.$$

This makes it possible to compute the wheel diameter necessary to obtain a given output, since if r_i is fixed for construction reasons, if ε is the ratio selected for S and the circle swept by the vanes, R may be obtained by the equality:

$$\varepsilon \pi (R^2 - r_i^2) = S.$$

S being obtained from the preceding equation.

It remains to determine the magnitude to be assigned to the various design characteristics in order to obtain optimum values for ρ_r and ultimately for ρ_m.

The principle elements will be:

The angle of incidence α, which varies along the radius.

The ratio m of the angular speed to the wind speed, which we will term the rating coefficient.

Normal wind: this will be considered to be the wind speed at which an assembly of given design permits a rating coefficient m corresponding to maximum efficiency.

II. Determination of Conditions for Maximum Efficiency. As we will see, these conditions are obtained by a specific distribution of incident angles along the radius in conjunction with a given rating coefficient.

Equation for the power developed by a working surface element. Let us consider the element ds defined above, and let us extend it in a plane tangential to a cylinder of radius r which we will take to be the plane of the diagram (Fig. 13).

This surface element becomes a small flat surface at an angle α to the direction of the wind.

Let E_1 represent this element, which moves with a tangential velocity u.

Let us consider the movement of E in relation to the direction XX' of V, by assuming a second position E_2.

It can be seen that the entire movement occurs as if the element had slipped $0_1 0_2$ in the direction of the wind with a speed /34 $\frac{u}{\tan \alpha}$. The relative wind speed in relation to this speed is thus $V - \frac{u}{\tan \alpha}$.

The thrust dS is normal, setting aside the friction of the air, and according to ordinary aerodynamics equations, its expression will be:

$$dF_0 = \lambda(\alpha) \varphi \left(V - \frac{u}{\tan \alpha}\right)^2 \sin \alpha \, ds.$$

$\lambda(\alpha)$ being a coefficient dependent on α;

$$\phi = 0.08.$$

The motive component perpendicular to XX' is thus:

$$dP_0 = \lambda(\alpha) \varphi \left(V - \frac{u}{\tan \alpha}\right)^2 \sin \alpha \cos \alpha \, ds,$$

or, according to the definition $m = \frac{\omega}{V}$,

$$dP = \lambda(\alpha)\varphi V^2\left(1 - \frac{mr}{\tan\alpha}\right)^2 \sin.\alpha\cos\alpha\, ds. \tag{1}$$

Since the element moves in the direction of this thrust at a speed u, the elemental power is dW = dP·u = mr·dP·V, or:

$$dW = \lambda(\alpha)\varphi V^3\left(1 - \frac{mr}{\tan\alpha}\right)^2 \sin\alpha.\cos\alpha.\, m.r.ds. \tag{2}$$

Elemental Efficiency. The kinetic energy of the air currents striking dS is:

$$dW_0 = \frac{\omega}{2g}\sin\alpha\, V^3 ds.$$

According to the definition given, the efficiency of the element will be: /35

$$\rho r = \frac{dW}{dW_e} = \frac{2g}{\omega}\varphi\lambda(\alpha)\, mr\left(1 - \frac{mr}{\tan\alpha}\right)^2\cos\alpha.$$

Let us assume $C = \frac{2g\phi}{\varpi} = 1.215$ and $\lambda(\alpha) = I$, since the incident angles involved here will always be greater than 45° (Soreau).

The equation for the elemental efficiency becomes:

$$\rho_r = Cmr\left(2 - \frac{mr}{\tan\alpha}\right)^2\cos\alpha. \tag{3}$$

The optimum angle at aidistance r from the axis can be determined as follows.

Given the rating coefficient $m = \frac{\omega}{V}$ which characterizes the speed of the motor, we now propose to determine the value of α which will yield a maximum ρ_r.

Cancelling the derivative of Eq. (3), one obtains the equation:

$$\tan^3\alpha \mp 3mr\cdot\tan\alpha - 2mr = 0,$$

which has a real root corresponding to a maximum for an angle located between arc tan mr and $\frac{\pi}{2}$.

The results are represented by the curves in Fig. 14, which give the optimum values of α for three specific values of m.

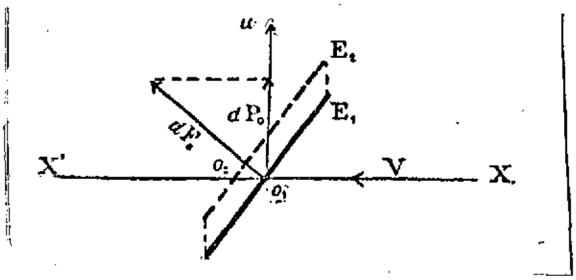

Fig. 13. Action of wind on an element.

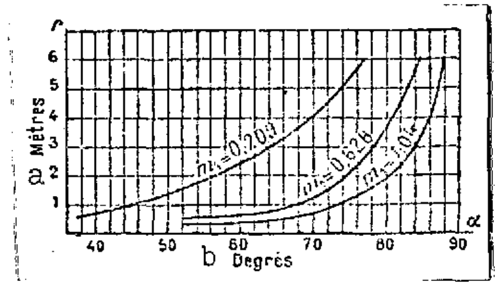

Fig. 14. Optimum value of α as a function of distance from axis.

Key: a. Meters. b. Degrees.

These coefficients m may be assumed to characterize an extremely slow, moderate or fast rate of operation for this type of motor: /36

For V = 10 m/sec:

m_1 = 0.209 yields N = 20 rpm

m_2 = 0.628 yields N = 60 rpm

m_3 = 1.04 yields N = 100 rpm

Maximum efficiency as a function of r. Let us continue to assume m given and the angles established in conformity with Fig. 14.

Using Eq. (3), we can calculate for each value of the radius the maximum efficiency whose variations as a function of r are represented by curves (3), which are plotted, however, without taking any functional energy losses into account.

An examination of Fig. 15 leads to the conclusion that the optimum efficiencies are obtained at the highest motor speeds in all cases. As a result, a consideration of the losses involved will show that with some radii, which are however greater than most ordinary dimensions, other more moderate motor speeds can also produce equally satisfactory results.

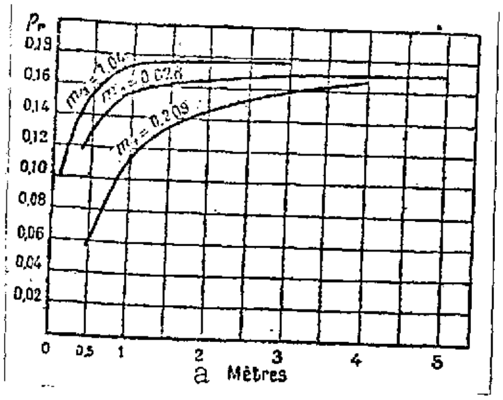

Fig. 15. Maximum elemental efficiency.

Key: a. Meters.

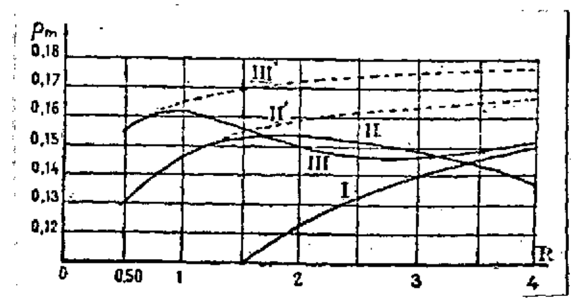

Fig. 16. Efficiency of entire assembly as a function of external radius.

If in addition we assign an absolute value to these theoretical efficiencies, we find that the efficiency cannot be expected to exceed 18% with assemblies driven by the thrust of the wind.

Maximum mean efficiency. The mean or overall efficiency has been defined by the equality:

$$\rho_m = \frac{1}{S}\int_{ri}^{R} \rho_2 \, ds$$

We will temporarily assume that the inside radius is zero and the projections of the working surfaces on the plane of the wheel will exactly overlap; one therefore has: $S = \pi R^2$ and $dS = 2\pi r \cdot dr$, and as a result: /37

$$\rho_m = \frac{2}{R^2}\int_{o}^{R} \rho_r \, r . dr.$$

ρ_m will obviously be at a maximum if the local efficiency ρ_r is as high as possible for each value of r.

We know that this would be the case with the three types of assemblies constructed with the angle distributions represented by curves I, II and III in Fig. 14 when these assemblies are operating at the rating coefficients m_1, m_2 and m_3, respectively. The elemental efficiency would thus be given by the curves in Fig. 15.

These curves can easily be represented by portions of hyperbolas, making it possible to integrate them into the above equation, and Fig. 16 (dotted curves) shows the maximum mean overall efficiency of the wheel as a function of the external radius R for the three types considered.

The unbroken curves represent the same efficiency, taking into account the losses which will be analyzed below.

III. Choice of Rating. Torque. Discussion. From now on consideration will be given only to wheels designed along the lines of types I, II and III, whose rate of operation can be varied as widely as necessary for practical purposes.

Let W equal the average output to be achieved. Assuming $r_i = 0$ and $\varepsilon = I$, the diameter 2R may be computed by the formula:

$$W = A \cdot R^2 \cdot \rho_m \cdot V_0^3$$

For this purpose we will choose a normal wind speed V_0, The optimum rating coefficient m will be made to correspond to this wind speed, as stated above, by means of a suitable arrangement of gears and cylinders, if a pump is involved.

We must now consider the type of wheel and the rpm which should be used. /38

From the standpoint of power, the preceding discussion has shown that a fast rpm will produce the highest efficiency. Setting aside the question of energy losses and keeping to a diameter of less than 2 m, the choice of assembly seems to be firmly established. However, it is still necessary to ensure that consideration of the starting torque, especially, will not show the fast type of assembly to be markedly inferior to other assemblies operating at a lower rpm and with smaller incident angles.

Torque. As we will see, an analysis of the torque at rest (starting) and during operation will make it possible to recognize the manner of variation of m and, ultimately, the efficiency ρ_m when the wind speed differs from the normal value V_0, which by definition is the wind speed of maximum efficiency.

The equations obtained above will now be used to discuss the characteristics of a wheel of ordinary diameter.

Specific moment. The elemental moment at a distance r from the shaft is:

$$M = dP \cdot r = r \varsigma \left(V - \frac{u}{\tan \alpha}\right)^2 \sin \alpha \cos \alpha_s ds,$$

All the vanes $ds \cdot \sin \alpha$ represent a circular ring $2\pi r \cdot dr$. Let us assume $V - \frac{u}{\tan \alpha} = v$ to be the relative wind speed at a distance r.

At V = 1 m/sec one has the specific moment:

$$M_1 = 2\pi\rho \int_0^R r^2 . \cos\alpha \, dr$$

α varying as given by the curves in Fig. 14. It is therefore possible to compute the following table.

TABLE 1

Radius of Wheel:	R = 0.5 m	1 m	2 m	3 m	4 m	5 m
Type I	M_1 = 0.015	0.128	0.81	2.34	4.7	8.08
Type II	0.013	0.086	0.47	1.11	2.32	3.8
Type III	0.007	0.056	0.26	0.63	1.16	1.89

Starting torque. – u = 0 v = V /39

$$M_0 = M_1 V^2$$

at a wind speed V.

Operating torque.

$$M = M_1 v_m^2 \; .$$

v_m being the mean relative speed between radii 0 and R.

On an intermediate radius r one has:

$$v_r = V - \frac{u}{\tan\alpha} \; .$$

The recoil velocity being:

$$\frac{u}{\tan\alpha}$$

The mean value of this recoil velocity may thus be written in the form $K\omega$.

For a given type of assembly, K depends only on R, the full radius of the wheel.

The moment of the operating torque will be:

$$M = M_1 (V - K\omega)^2 .$$

the values of K being given in Table 2.

TABLE 2

R	0.5 m	1	2	3	
	K = 0.815	1.142	1.175	1.209	Type I
	0.3	0.54	0.54	0.542	Type II
	0.145	0.23	0.27	0.286	Type III

Various formulas as a Function of M_1

Power

$$W = M_1 (V - K\omega)^2 \omega \tag{4}$$

Efficiency /40

$$\rho_m = \frac{M_1}{A}(1 - K\,m)^2 m \tag{5}$$

$$A = \frac{\varpi}{2g} \pi R^2.$$

This last equation is used to compute K. This is because with Type II, for example, when m = 0.628, we know that the efficiency ρ_m is given as a function of R by curve II in Fig. 16, and K may thus be derived from Eq. (5).

Variations in m and in the efficiency with wind intensity. Let us assume the motor torque to be constant, whether the load torque actually is constant or whether its variations areemade uniform by the rotation of the wheel, serving as a flywheel. In other words, here we will not be considering the operation of the assembly during startup or a radical slowdown.

One thus has:

$$M = M_1 (V - K\omega)^2 = \text{constant}$$

and as a result, M_1 being constant for a given assembly:

$$m = \frac{1}{K} - \frac{b}{V} \tag{6}$$

This equation gives the variations of m as a function of V.

b may be computed by assuming that with a normal wind, the rating coefficient m will assume a value corresponding to maximum efficiency. The choice of normal wind is thus extremely significant, since it determines the manner of variation of m during operation. If m were to remain constant at the optimum value, the efficiency would also remain constant and maximum, and when V decreased to below the normal wind speed, for example, the output would decrease directly with V^3. This alone is a considerable decrease, but if m were to change in the same case, the efficiency itself would decrease rapidly and the speed would immediately drop to an extremely low level.

The stability may be determined by the equation:

$$\sigma = \frac{1}{\frac{dm}{dV}} = \frac{V^2}{b}.$$

At a given wind speed, the stability increases as b becomes smaller. Since b depends on the normal wind speed, it would thus be advantageous to avoid assigning too high a value to the latter quantity. /41

Wind of minimum intensity. Here we will assume the motor torque to be constant until the assembly is stopped, which is generally not the case with pumps.

The assembly is halted when m = 0 or V_1 = Ab.

There is little variation in V_1 from one type of wheel to the next at a given normal wind speed and a given diameter, as will be seen from an example which will be given later on.

Application to discussion of the characteristics of a wheel. Let us consider a wheel with an external radius R = 1 m, and with the design characteristics of Types I, II and III.

For purposes of this discussion we will assume that the shaft of the receiver rotates at the same speed for any given type of wheel.

Let V = 7 m/sec and Ω (receiver) = 1.463 (approximately 15 rpm).

Thus the respective angular speeds of wheels I, II and III will be:

$\omega_1 = 1.463$ $\omega_2 = 4.4$ $\omega_3 = 7.3$

The reduction coefficients will be:

$\psi_1 = 1$ $\qquad\qquad$ $\psi_2 = 0.333$ $\qquad\qquad$ $\psi_3 = 0.2$

Power. At a normal wind speed $V_0 = 7$ m, the equation $V = AR^2 c_n v_0^3$ yields:

$W_1 = 5.256$ $\qquad\qquad$ $W_2 = 9.59$ $\qquad\qquad$ $W_3 = 11.5$

As we predicted, fast wheels are much more powerful.

Starting torque on the shaft of the receiver. M being the starting torque on the shaft of the wheel, on the shaft of the receiver M will be:

$$\mathfrak{M} = \frac{M_0}{\psi} = \frac{M_1}{\psi} V^2.$$

In the present case, the wind speed is assumed tobbe $V_0 =$ 7 m.

$\mathfrak{M}_1 = 6.27$ $\qquad\qquad$ $\mathfrak{M}_2 = 12.6$ $\qquad\qquad$ $\mathfrak{M}_3 = 13.72$

Although the specific moment of the Type I wheel is more than twice that of Wheel III, the latter allows better starting due to /42
the greater reduction required by its fast rpm.

Stability. With a 7 m/sec wind one obtains:

$\sigma_1 = 10.45$ $\qquad\qquad$ $\sigma_2 = 4.4$ $\qquad\qquad$ $\sigma_3 = 2.12$

In this respect the slow wheel is superior, since with the fast wheel the power decreases very quickly as the wind becomes gentler.

Minimum wind speed. Using a normal wind speed $V_0 = 7$ m:

$V_i(\mathrm{I}) = 5.36$ m $\qquad\qquad$ $V_i(\mathrm{II}) = 5$ m $\qquad\qquad$ $V_i(\mathrm{III}) = 5.34$ m

With a normal wind speed $V_0 = 5$ m:

$V_i(\mathrm{I}) = 3.8$ m $\qquad\qquad$ $V_i(\mathrm{II}) = 3.57$ m $\qquad\qquad$ $V_i(\mathrm{III}) = 3.8$ m

Choice of normal wind. To what wind speed should the rpm yielding maximum efficiency be matched?

Let us consider two type II wheels driving pumps and let us assume that the cylinders have been designed in such a way that the optimum rpm m = 0.628 is obtained with wind speeds of 7 and 5 m, respectively.

Let us examine the results of these assumptions:

In the first case one obtains a theoretical halt at V_1 = 5 m, and in the second at V_1 = 3.6 m. As for the power, this will vary as shown in Fig. 17. The following observations may be made upon examination of this figure:

By assuming a normal wind speed V_0 = 5 m, one obtains the most complete utilization of low summer winds of 3.50 to 7 m/sec, part of which would be unusable in the first case. However, the power is still virtually the same under a 7 m/sec wind as it would be if the latter speed had been taken as the normal wind speed. /43

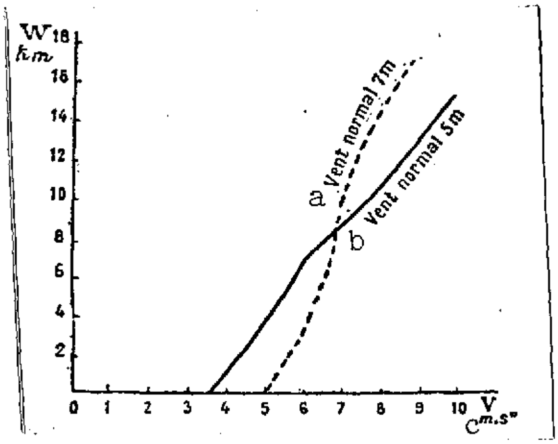

Fig. 17. Power of a 1 meter wheel, Type II.

Key: a. Normal wind, 7 m.
b. Normal wind, 5 m.
c. M/sec.

Finally, the mean power within the usable range, that is from 3 m to 9 m, is appreciably the same in both cases.

Choice of V = 5 therefore offers all the possible advantages.

IV. Energy Losses. In the case of a wheel with a number of blades separated by small intervals, the resistance of the air in the ordinary sense of the word, that is, the force opposing movement in an undefined atmosphere, has very little influence. As for the disturbance caused by the tipss of the vanes, which constitutes an energy loss, this may be prevented in large part by means of light hooping.

One important cause of power dissipation, on the other hand, seems to be the eddies produced by the assembly as it moves. The wind motor actually operates as a helicoidal fan, driving the air out from between its blades at a given speed.

In addition, this air is thrust radially by centrifugal force. We will overlook this centrifugal effect, which can be neutralized by the hooping mentioned above, in favor of a more specific analysis of the helicoidal eddies in which the fluid travels; the angle of these helices depends on the incident angle and the radial distance r.

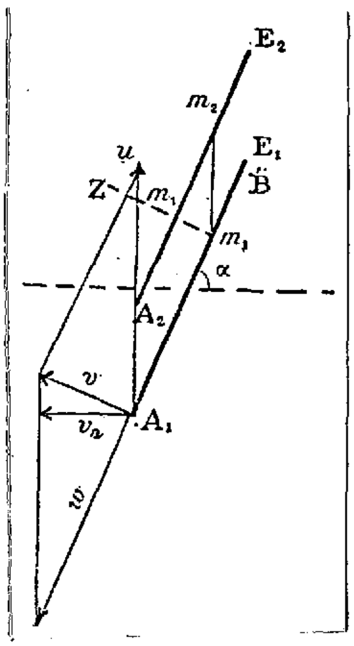

Fig. 18. Losses due to propulsion.

Let us consider two blade elements at a distance r, as shown in Fig. 18. When element E, traveling at a tangential speed u, encounters an air molecule m_1, this molecule is thrust toward A_1, passing over portion m_1A at a relative speed w, while, assuming zero friction, it describes the absolute trajectory m_1Z. A molecule arriving at A_1 will thus possess an absolute speed v of direction normal to E_1 and having the components u and $\bar{w}$. Assa result:

$$v = u \cos \alpha.$$

Let us consider the surface unit on the rear face A_1A_2 of the wheel. The component of $\bar{v}$ normal to A_1A_2, or flow component, will be: /44

$$v_n = u \cos \alpha \sin \alpha$$

The mass flow of the air driven across the vertical surface unit is therefore:

$$q_m = \frac{\bar{\omega}}{g} u \cos \alpha \sin \alpha.$$

The propulsive energy being:

$$E_v = q_m \frac{v^2}{2} = \frac{\bar{\omega}}{2g} u^3 \cos^3 \alpha \sin \alpha.$$

If η is the ratio of this lost energy to the energy of the wind $\frac{\tilde{\omega}}{2g}V^3$ acting on the surface unit of the forward surface, one obtains:

$$\eta = \frac{u^3}{V^3} \cos^3 \alpha \sin \alpha = (mr \cos \alpha)^3 \sin \alpha \qquad (7)$$

and, taking only this cause of losses into account, the efficiency at a given point is characterized by the magnitudes r and α:

$$\rho_p = \rho - \eta$$

It may be noted in passing that this loss coefficient η increases with the rating coefficient m and the radius, but decreases as the incident angle α increases. Now, since α (see Curves I) does actually increase with m and the radius, there is thus some compensation for wide-diameter wheels. To reduce this loss, therefore, the posterior part of the vane can be curved inward to increase α in this region.

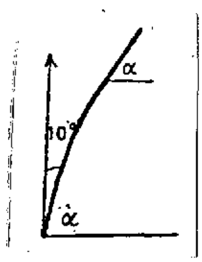

Fig. 19. Incurvated profile.

It would even appear that α should be increased to its maximum value of 90° in order to cancel speed v. Nevertheless, since it is a good idea to ensure the discharge of the air, which tends to escape along the working surface due to the pressure differential between the front and rear surfaces of the wheel, and to recover part of its energy, it should be to advantage to allow the tangent to the discharged air /45 to make a given angle with the peripheral speed in a manner similar to that of a turbine blade, that is, 10° for this angle and α' = 80°.

It may be noted that under these conditions the vane will once again be straight with large radii, where the angle of attack is close to 80°. To determine the significance of this loss, one may refer to Table 3 to see how the elemental efficiency is affected by eddies computed on the basis of Eq. (7) in the case of vanes with a straight profile.

TABLE 3

r (distance from shaft shaft)	0.50 m	1 m	2 m	3 m	
Type I	0.058	0.113	1.145	0.158	ρ without losses
m = 0.209	"	"	0.136	0.145	ρ_p with losses (7)
Type II	0.134	0.158	0.165	0.17	ρ
m = 0.628	0.127	0.137	0.121	0.112	ρ_p
Type III	0.17	0.173	0.176	0.178	ρ
m = 1.04	0.142	0.14	0.138	0.15	ρ_p

In regard to Type II, for example, the efficiency for $r = 1$ is decreased by 12%, and with Type III, by 18%.

As for the problem of improving the efficiency, our theoretical findings show that the element under consideration will be counterbalanced by the eddies as its distance from the axis increases, to the point that the efficiency is lower at 3 m than at 1 m with Type II. Thus there is a sort of equivalence with Type II, with the efficiency undergoing little variation along the radius, up to 3 m.

Fig. 16 gives the mean or overall efficiency for wheels with diameters of 0 to 10 m (R = 5 m) in the case of vanes curved to the rear in such a way that the exit angle = 80° (plotted as an unbroken line).

Choice of rpm, taking losses into account. The theoretical curves given in Fig. 16 (dotted lines) indicate consistently higher efficiency for Type III at the rating m_3. We are now capable of revising this judgment to some extent, allowing for the fact that, given equal efficiency, the slower assembly will require less careful construction, will undergo less wear and tear, and consequently will be preferable. After examining Fig. 16 (unbroken line), we can thus choose the rpm in the following manner: /46

Diameter

D = 1.20 to D = 3 meters (usual case).	Type III: m = 1.04
D = 3 m to D = 6 m	Type II: m = 0.628
D greater than 6 m.	Type I: m = 0.229

It may be noted that with a suitable choice of assembly type, one can count on a mean overall efficiency of 0.15 in all cases, which will facilitate preliminary design. If W is the power to be obtained with a wind V_0, R can be computed by the formula $W = 0.15\ AV_0^3\ \varepsilon\ R^2$. It is then possible to select the assembly type and the corresponding rating m.

Spacing of vanes. The efficiency of a windmill with a large number of vanes is frequently said to be lower than that of an assembly whose vanes are set at wide intervals. However, as we have already pointed out, our main concern is the ratio of the useful power to the size of the assembly, or in other words, the circle swept by the blades. Consequently it is advantageous to place the largest possible number of working surfaces within this circle, even though the individual efficiency may be lower, rather than to use four widely-spaced blades, operating at high efficiency but occupying only a small part of the circle.

One satisfactory solution from an aerodynamic standpoint would obviously be the use of a single helicoidal surface with variable pitch, offering complete utilization of the cylinder of air bounded by the outermost contour of the assembly. Construction would be difficult in this case, however.

Nevertheless it would be to advantage to decrease the number of vanes, provided their area is increased, as long as the resultant construction problems do not appear to be excessive.

With ordinary wheels having 18 or 20 blades, which are extremely easy to construct, a gap corresponding to $\varepsilon = 0.75$ should be adequate to prevent any detrimental effect of one vane on a /47
neighboring vane, at least to a large extent.

Since this effect could undoubtedly result in the partial reciprocal cancellation of the overpressure on the forward surface of one vane and the negative pressure on the back of the following vane, it may be assumed that the high-incidence types, such as III, whose aerodynamic surface is nearly vertical, should permit a much more contiguous arrangement while retaining an efficiency quite close to the computed value. This would therefore be another point in their favor.

Conclusions

According to the results of this study, the characteristics of a wheel with satisfactory efficiency may be summarized as follows.

1. The rotation speed N should be chosen with respect to the diameter, by selecting an appropriate rating:

$$m = \frac{2\ N}{60\ V_0} = \frac{\omega}{V_0}$$

V_0 theoretically varying no more than $\pm$ 5 m/sec.

2. The selection of m involves the choice of a type of vane characterized by a given distribution of incident angles along the radius. The profiles are incurvated to the rear.

Under these conditions, the maximum efficiency is 0.15 under normal winds.

Fairly precise rules of construction must therefore be laid down, but these assemblies remain limited to low-power usage. On the other hand, they are able to operate day and night without any monitoring or maintenance costs, and they are extremely simple in design.

Nevertheless it is unfortunate that such a low-density fluid, and one which is available absolutely without cost, must be used in a machine whose efficiency is so low.

In a 7 m/sec breeze, a 1 hp motor will require a wheel 6 m in diameter, which would be extremely cumbersome; if the efficiency could be raised to 60%, the diameter would be only 2.70 m.

However, we have seen that the theoretical efficiency can be no higher than 18% and that the low efficiency of these devices is due to the very nature of their mode of operation.

It is therefore necessary to look for assemblies of another type than those using the direct thrust of the wind. Apparently it should be possible to use turbines, which are theoretically capable of high efficiency. The problems involved in capturing wind energy appear to arise from two main causes: the irregularity /48 of the direction of the fluid as it enters the blades, and its high mobility, which generates vortices.

The best mode of operation would seem to consist of two phases:

1. The conversion of the kinetic energy of the wind into static pressure.

2. The use of this pressure in a strong-reaction turbine. This problem merits the attention of designers, since so far American imports have dominated our supply of these assemblies, while the lower cost price of the national production, free of freight charges, should leave a margin permitting the realization of an assembly, even a more complex one, whose output would be higher."

This is completely accurate. In the Oise, Aisne and Seine-et-Oise Departments, we have seen wind motors with a number of simple galvanized sheet metal blades built by the Cyclone Co. in Compiègne and by the Etablissements Chêne of Saint-Quentin and American "Aermotors," starting under extremely light winds and driving a pump or generator for several days and nights in cases where windrmotors with four or six blades would remain motionless. The latter are preferable in high-wind areas such as the seacoast or the mountains, where periods of calm are somewhat rare.

Starting in a low wind requires: low wheel inertia and light mounting and blades, the latter constructed of thin sheet metal; perfect balancing and all bearings on balls or rollers, those of the wheel shaft as well as those in the transmission.

With these requirements, low winds can be used. These are the most frequent in occurrence in France, where the terrain is interrupted by numerous hills and mountains.

Equations given by Commander Riet: P in horsepower:

American wheel with numerous blades:

$$P = \frac{SV^3}{1500}$$

An area of 12 m^2 will develop 1 hp in a 5 m/sec wind.

Windmillsdesigned by Prof. La Cour, with four vanes (Figs. 6 and 7): /49

$$P = \frac{SV^3}{1250}$$

One horsepower with 10 m^2 in a 5 m/sec wind.

Soerensen six-vane windmill (Fig. 46):

$$P = \frac{SV^3}{600}$$

Here, with equal area, the power is 2 1/2 times that of the American turbine.

The Constantin turbine, with two or four blades identical to those of aircraft propellers; this assembly is not yet commercially available, but its formula would be:

$$P = \frac{D^2V^3}{500}$$

With equal diameter, its output would thus be three times that of the American turbine (Fig. 56).

However, as Commander Riet states, the American turbine has the advantage over all other systems of being able to start in winds as low as 2.50 to 3 m/sec.

According to Houard and Lémonon, the following results are obtained with a 10 m/sec wind.

Diameter of Wind Wheel	Rpm	Output in hp
2.45 m	75 to 80	0.50
3.00 m	70 to 75	0.70
3.65 m	65 to 70	1
3.90 m	60 to 65	1.40
4.25 m	55 to 60	2
4.85 m	50 to 55	2.80
5.45 m	45 to 50	3.70
6.00 m	40 to 45	4
7.60 m	35 to 40	6
9.15 m	30 to 35	8

POWERING OF GRAIN WINDMILLS AND AGRICULTURAL MACHINES, ACCORDING TO THE SACHSICHE STAHL-WINDMOTOREN FABRIK OF G. R. HERZOG, DRESDEN /50

Diameter of Wheel in m	With Agricultural Implements, Replacement of:	For Millstones with a Diam. of:	For Rollers for Crushing Grain, per hour: Fine Ground	Coarse Grnd
4	Hand labor.	0.4 m	60 kg	80 kg
5	1 to 2 hp	0.5 m	150 kg	300 kg
6	2 to 3 hp	0.6 m	175 kg	350 kg
7	3 to 4 hp	0.8 m	200 kg	400 kg
8	4 to 5 hp	1.0 m	250 kg	500 kg
9	5 to 6 hp	1.25 m	300 kg	600 kg
10	6 to 7 hp	1.50 m	450 kg	900 kg
11	7 to 8 hp	1.75 m	600 kg	1,300 kg

ROTARY MOTION ASSEMBLIES AND THEIR OUTPUTS (CYCLONE, COMPIEGNE)

Wheel Diameter	Output in Horsepower Under Winds Speeds of: 4 to 5 m	6 to 7 m	8 m
5.20 m	1 3/4	3	4 1/2
6.50 m	1 3/4	4 1/4	6 1/2
8 m	2 1/2	6	8
10 m	4	8	12
12 m	6	12	18

OUTPUT OF THE "HERKULES" [?] WIND MOTORS PRODUCED BY THE VEREINIGTE WINDTURBINEN WERKE, DRESDEN /51/

Diameter of Turbine		Output in Horsepower Under Wind Speeds of:		
In meters	In English feet	5 m/sec	6 to 7 m/sec	8 m/sec
2 1/2	8	1/6	2/3	3/4
3	10	1/4	3/4	1
3 1/2	12	1/3	1	1 1/4
4	13	1/2	1 1/2	2
4 1/2	14	3/4	2	3
5	16	1	2 1/2	4
5 1/2	18	1/1/4	3	5
6	20	1 1/2	4	6
6 1/2	21	1 3/4	4 1/2	7
7	22	2	5	8
7 1/2	24	2 1/4	5 1/2	9
8	25	2 1/2	6	10
8 1/2	26	2 3/4	6 1/2	11
9	30	3	7	12
10	32	4	8	14
11	36	5	10	15
12	40	6	14	20
13 1/2	43	8	19	28
15	50	10	25	36

Information to be supplied to the designer of a wind motor to be used for drawing water, sprinkling, irrigation, draining of swamps, submersion of grapevines or supplying of water to farms, homes or factories (Fig. 20): /53

1. The amount of water to be drawn per minute or per day.

2. The height above ground to which it is to be raised (D).

3. The total depth of the well (A).

4. The average height of the water in the well (G).

5. The length of the delivery pipe (E).

OUTPUT CHARACTERISTICS OF THE HALLADAY WINDMILLS (FIG. 33) WITH DIFFERENT WIND SPEEDS

Outside Diam. of Blades	Inside Diam. of Blades	Total Area of Blades	Output of Wind Motor in hp/sec at wind speeds of: 3 m	4 m	5 m	6 m	7 m	8 m	9 m	10 m	Rpm under an average wind of 7 m/sec
2.400 m	0.750 m	4.100 m^2	0.02	0.05	0.09	0.15	0.21	0.37	0.55	0.70	60
3.000 m	0.850 m	6.500 m^2	0.04	0.09	0.20	0.30	0.50	0.70	1.04	1.43	52
3.600 m	1.650 m	8.400 m^2	0.06	0.15	0.30	0.50	0.74	1.13	1.61	2.20	47
3.900 m	1.800 m	9.400 m^2	0.07	0.17	0.34	0.59	0.90	1.45	1.99	2.72	44
4.250 m	1.150 m	13.140 m^2	0.10	0.25	0.49	0.85	1.30	2.01	2.80	3.90	42
4.850 m	1.240 m	17.260 m^2	0.15	0.35	0.68	1.17	1.80	2.70	3.84	5.50	37
5.500 m	1.750 m	21.350 m^2	0.17	0.40	0.87	1.49	2.31	3.56	5.06	6.95	32
6.000 m	1.750 m	25.860 m^2	0.23	0.55	1.08	1.86	2.88	4.42	6.31	8.60	30
7.600 m	4.400 m	30.160 m^2	0.35	0.66	1.30	3.00	3.40	5.30	7.50	10.00	21
9.150 m	4.400 m	50.550 m^2	0.50	1.10	2.20	3.80	5.90	9.00	13.00	17.00	18

/52

6. The height of obstacles around the well which shelter it from the wind (trees, houses, elevations in the terrain) (F).

7. The distance of these obstacles from the site chosen for thewwindmill (G).

8. Whether the windmill should be built on anstructural iron pylonwoakmasonry tower or a reinforced concrete pylon/tank.

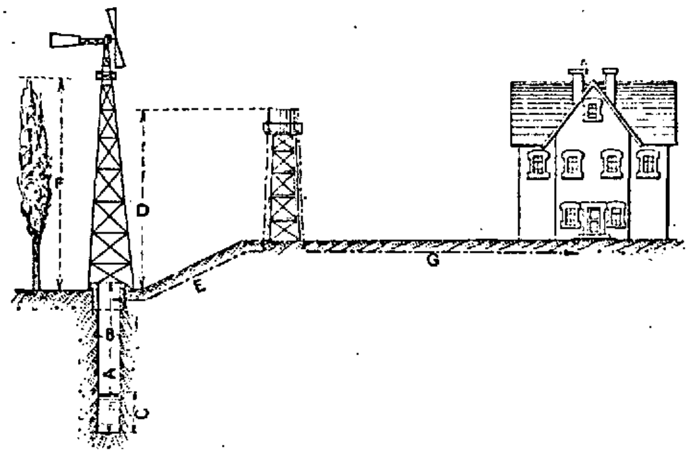

Fig. 20. Installation diagram.

Information to be supplied for an electrical installation:

The number of lamps powered by the installation.

The number of lamps illuminated at one time each day.

The number of hours per day for which they are on.

The luminous intensity. /54

The distance of the pylon from the buildings lighted.

Whether the wind motor is to be installed on an elevation, on flat land or in a valley.

The approximate height of surrounding obstacles within a radius of 150 to 200 m.

Chapter 3

MULTIPLE BLADE WIND MOTORS

The Henry "Venetian Blind" blade wind motors, Boulogne-sur-Seine

The blades of this assembly are made of wood and are /55
mounted on an octagonal steel frame (Fig. 21). Orientation is obtained by means of a rudder G and the assembly turned aside from the wind by means of a lateral aileron P returned to position by a counterweight C at the end of the lever.

The energy from the hand crank on which the paddle wheel is mounted is transmitted through a vertical rod and pin to a pump installed in the center of the base of the pylon.

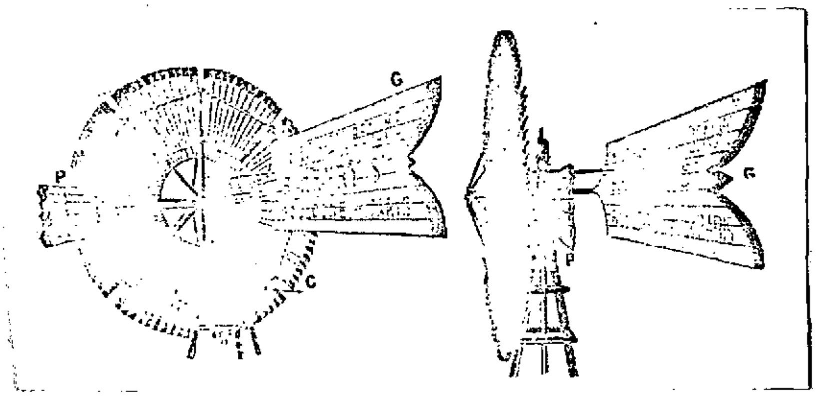

Fig. 21. Multiple wooden blades on a steel framework

Generators with sheet steel blades

All wind generators of American design (Aermotor, Gold Shapley and Muir, Flint and Walling, etc) some of German design (Adler), those of English design and most of French manufacture are built with multiple blades (18-30, depending on the diameter of the wheel) which are more or less concave on the windward side. Their length is approximately 2/3 the /56
radius of the wheel and they are affixed to a circular frame made up of flat steel bars.

Fig. 22 shows a wheel assembly manufactured by Aermotor of Chicago and Fig. 23 a detail showing how the incurvated steel sheats are attached, by means of a rib C placed against the surface confronting the wind.

The effect of this rib is to increase the eddies behind vanes, which detract from the efficiency.

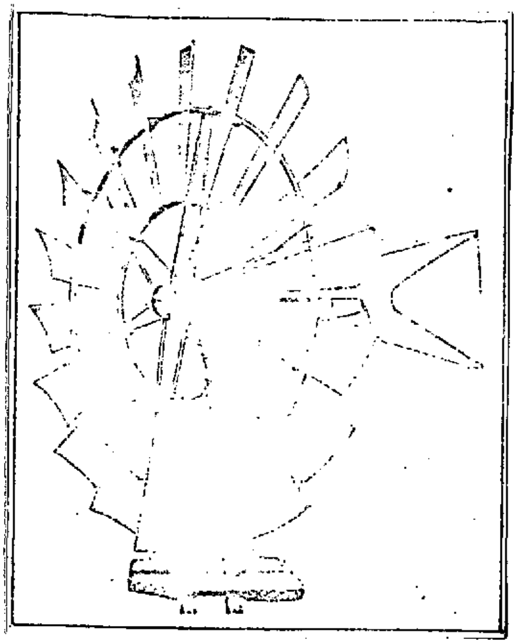

Fig. 22. Sheet steel blades

Fig. 24 shows the framework of a wheel 7.50 m in diameter, manufactured by Cyclone of Compiègne.

All these assemblies are oriented by means of a rudder; Fig. 25 shows the details of construction of this device.

The assembly is generally /57
turned aside from the wind by the use of a horizontal shaft for the wheel which is off-center in relation to the vertical pivoting shaft. Fig. 26 shows this device on a Cyclone (French) and Fig. 27 on an Aermotor (American).

Other manufacturers, such as the Etablissements Chêne in Saint-Quentin, Henry, Vereinigte Windturbinen in Dresden, and F. Koster, of Heide, Holstein, use a fixed aileron in the plane of the wheel (Fig. 45).

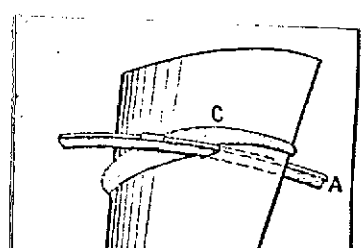

Fig. 23.

The use of a wheel off-center from the axis of the pylon does not allow for the direct control of the vertical rod. Therefore there must be a gear train between the shaft of the wheel and the hand crank which activates the rod.

For this direct control, it is necessary to use a lateral aileron system to shield the wheel from the wind; in addition, this
type of system is less costly to /58
build than the excentric system.

The rudder is generally returned to its position perpendicular to the plane of the wheel by means of a long spiral spring (Fig. 26). In the

Aermotor (Fig. 27), a shock-absorber spring is opposed to the action of this draw-back spring, while a few designers (Couppez in Paris and Henry [Fig. 21], among others) used a counterweight with lever.

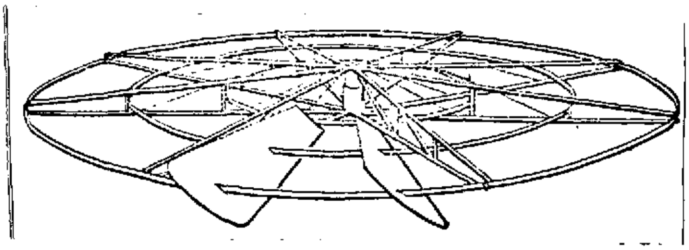

Fig. 24. Framework of a wheel 7.50 m in diameter (Cyclone).

The wheel may be furled or turned aside from the wind from the foot of the pylon by means of a steel cable wound onto a winch (Fig. 28).

Inclination of the shaft of the paddle wheel toward the horizon, which is advantageous from the standpoint of efficiency, is possible only when the transmission to the ground consists of a vertical shaft or when there is a generator at the base of the main shaft (see Chapter 8 on Transmission Systems).

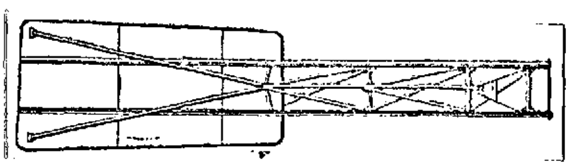

Fig. 25. Rudder for orientation

The head of the wind meter at the top of the pylon is pivoted by means of ball bearings or rollers; Fig. 9 shows a detail of this mechanism on a Cyclone assembly (French) and Figs. 30 and 31 on an Adler (German).

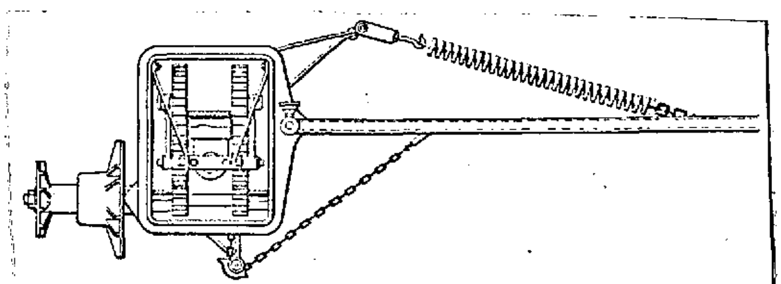

Fig. 26. Mechanism (Cyclone) for wheels 2.80 to 5.70 m in diameter (with rod).

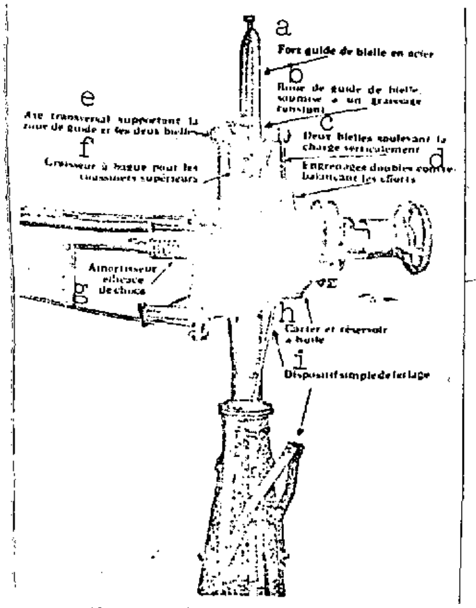

Fig. 27. Mechanism of the Aermotor (with rod).

Key:

- a. Heavy steel guide for rod
- b. Guide wheel for rod, with continuous lubrication
- c. Two rods raising the load vertically
- d. Double gears counter-balancing stresses
- e. Transverse shaft supporting the guide wheel and the two rods
- f. Ring lubricator for upper journal boxes
- g. Effective shock absorber
- h. Gearbox and oil tank
- i. Simple furling device

The cable or connecting /59
rod which serves to control the furling of the wheel from the ground will obviously be unable to follow the rotational movement of the windmill around its vertical axis. As a result, this cable is divided into two branches which are secured to a ball race to the upper part of which are attached two chains or cables which activate the rudder. The movement of the cable on the ground may thus be transmitted to the chains of the rudder, which turn only with the head of the wind motor.

Figs. 29 and 31 show the cables and chains involved.

Halladay windmill with improvements by Schabaver of Castres (Tarn) (Fig. 33).

Fig. 34 shows the details of this assembly:

A) Cast steel* platform attached to two vertical girders connected to two other horizontal girders /60
imbedded in the pylon or tower.

This platform is reinforced by two bars (E) which connect two other points in the circumference opposite the two girders, thus giving it four points of support. This platform serves as a roller-track

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*[Translator's note: or cast iron.]

for the rotating platform B, which is made up of two parts:

1. A ring of bevel rollers similar to those of railway turntables.

2. The moveable platform itself. This part is able to move in all directions around its center due to the rudder (V) at the rear, and the vanes are thus in an appropriate position to receive the direct thrust of the wind.

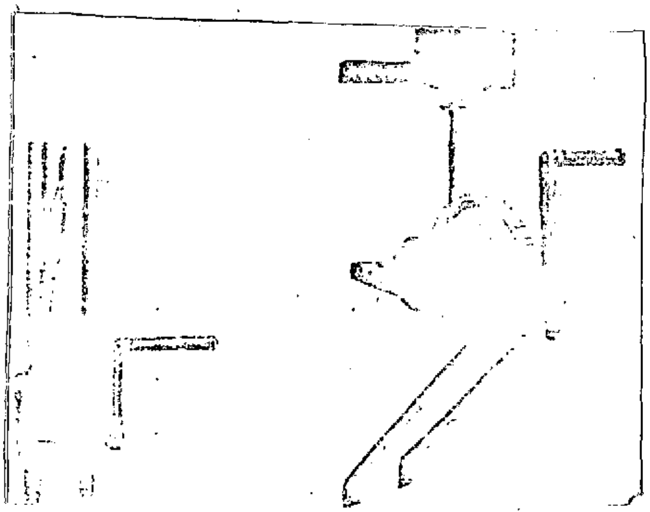

Fig. 28. Winches for the cable controlling the turning aside of the wind wheel (F. Köster).

The edge of the platform /61
is flanged downward to protect the lower table and the rollers against water and any foreign bodies which might hinder the rotation of the assembly.

The platform is equipped with anti-friction journal boxes which receive the horizontal shaft. The excentric disc (M) which transmits the movement of the rod (L) is attached to the end of this horizontal shaft. At the other end of the shaft is a star wheel (CC) with each of its arms attached to one of the windmill vanes. No matter what positions are occupied by the rotating platform (B), which determines the rotational movement of the rod (L), the pump is kept in regular operation by means of the bearing (S) and its ring, forming a journal bearing, the regulator (Z), which regulates the stroke, and the joint (X) on which the bar which passes through the bearing and the regulator is rotated. One advantage of this arrangement is that it does not prevent the automatic expansion or folding of the vanes by stopping the connecting rod (R).

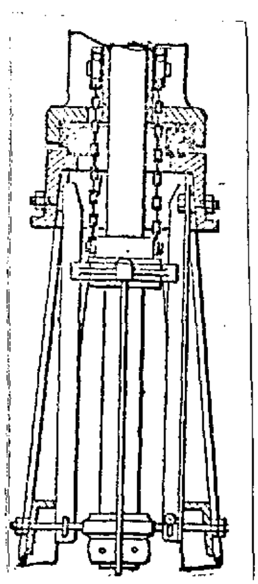

Fig. 29. Head of the Cyclone wind generator.

connecting rod (R).

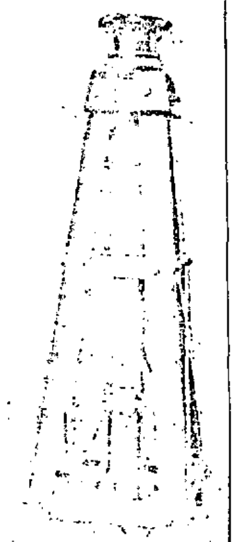

Fig. 30. Ball bearing for head of pylon.

Fig. 31. Head of pylon and foundations of wind wheel.

Fig. 32. Connection of reinforcing rods or cables of pylons (F. Köster).

The unusual characteristic of the Halladay windmill is the vane regulator (Figs. 33 and 34).

In front of the CC star wheel on the drive shaft there are six bent levers (Y), whose /62
outside ends are connected to the vanes by an iron rod which opens or closes them; the other end, which is much shorter, is connected by a small rod to the ring D which moves on the shaft. This ring moves inside a larger fixed ring, which , equipped with a forked bent lever E and counterweight W, controls the opening of the shutters.

At the outward ends of the rods which maintain the shutters there are weights whose purpose is to decrease the area of the vanes presented to the wind as the wind speed increases beyond a given limit. The effect of these control weights is exactly opposite to the that of the counterweight W, which tends to open the vanes as the speed of the wind increases. With this design, the Halladay windmill is able to operate at a uniform speed no matter what the wind speed may be.

To stop the windmill and close the shutters, one need only draw down the connecting rod R and fasten it at the end. This connecting rod, which communicates at N with the lever F through the rod R and the counterweight with chain Q, moves the disc D to the rear and closes the shutter. The only purpose of the weight O is to cancel the weight of the rod R and R'.

It may be noted that the regulator DY establishes direct communication with each shutter, and sets up direct action of the control weights of the shutters on the moveable part and its joints. In this way, it gives positive movement to all the parts of the assembly.

Since these parts operate when the wind is quite high, wear and tear is minimal.

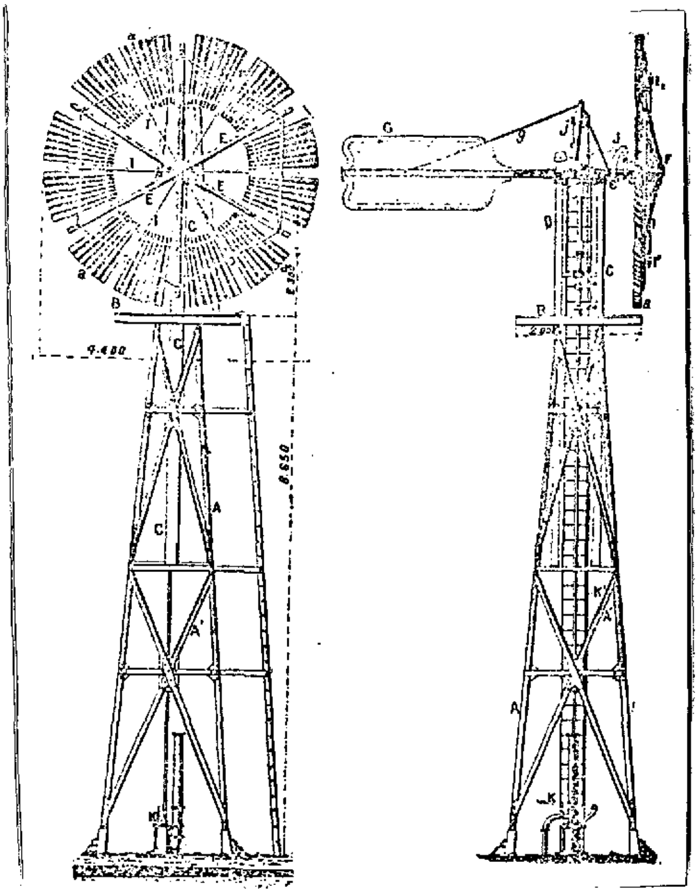

Fig. 33. Halladay windmill facing into the wind.

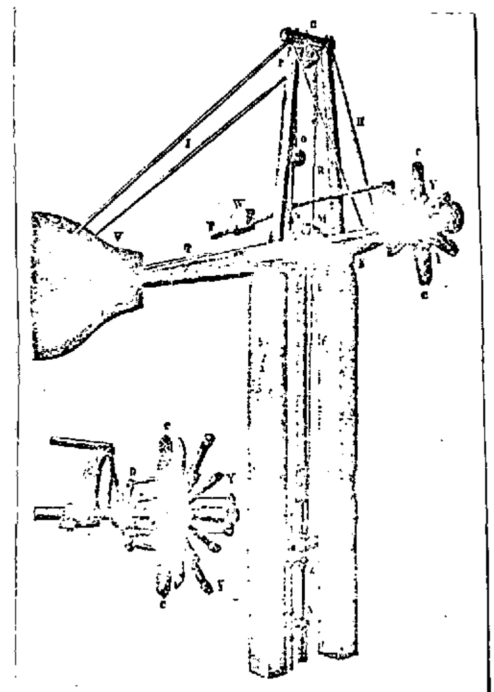

Fig. 34. Details of the Halladay windmill.

Thousands of copies of this windmill, of all diameters, have been built in both France and the U.S. Because of its excellent efficiency the Americans have given it the name "Standard."

Twin Wheel Wind Motors

The Twin Wheel Manufacturing Company of Hutchinson, Kansas, has an assembly with two so-called "twin" drive wheels mounted on /63
a single pylon, as shown by the schematic diagram in Fig. 36. The rectangular fram b on which the horizontal shafts of these two wheels are mounted is installed on a rotating platform p; this frame is reinforced by an angle-iron superstructure z.

The two wheels rotate in opposite directions and drive a shaft a by means of two pairs of bevel pinions u u. Through a pinion with righthand toothing, the shaft a drives the toothed wheel keyed into the crankshaft i, which activates the connecting-rod t

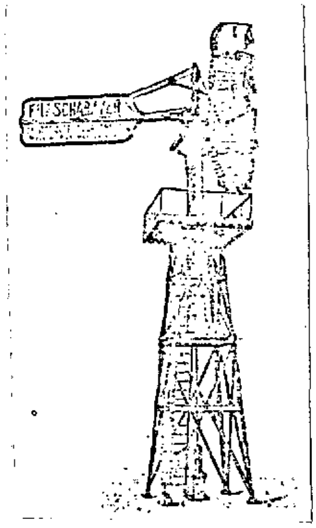

Fig. 35. Halladay windmill turned aside from wind.

of the pump through two upper rods. This mechanism is similar to that of the American "Aermotors."

The assembly is oriented by means of a rudder q with an articulation at o and held in a perpendicular position on the frame b by a spiral spring r.

The assembly is turned aside from excessive winds by means of a fixed aileron e; the rudder q can be brought into the plane of this aileron at will by pulling on a chain c which makes it possible to stop the windmill by placing its /64 wheels in the direction of the wind. The Twin Wheel Company states that its windmill is the most powerful in the world, a result of its wheel diameter, which actually is quite small: 8 ft, i.e., 2.44 m; 10 ft, i.e., 3.04 m; and 12 ft, i.e., 3.65 m for the three models which have been built. Obviously, however, with two wheels the output will be twice that of an assembly with one wheel. However, the mechanism is complex and it would be simpler to increase the diameter of a single wheel as most designers do.

The Bollée Wind Generator with Governing Blades

The following documents on the origin of the Bollée wind generator have been supplied to us by Mr. Amédée Bollée of Mans (Sarthe):

Patent, applied for March 30, 1868, by Ernest Bollée, and issued June 9, 1968.

Patent 167726, applied for March 17, 1885, by Auguste Bollée, son of the above; probable date of issuance August 4, 1885.

In the first document a claim is entered for the use of a fixed "governing" wheel equipped with curved vanes designed to direct air currents perpendicular to the plane of each vane on the drive wheel located to the rear and on the same horizontal shaft, "in such a way as to influence the movement of this wheel as directly as possible." The drive wheel is connected to the transmission by a bevel gear, and to compensate for the drive torque, which prevents the drive wheel from "standing completely perpendicular to the direction of the wind," Bollée has placed its

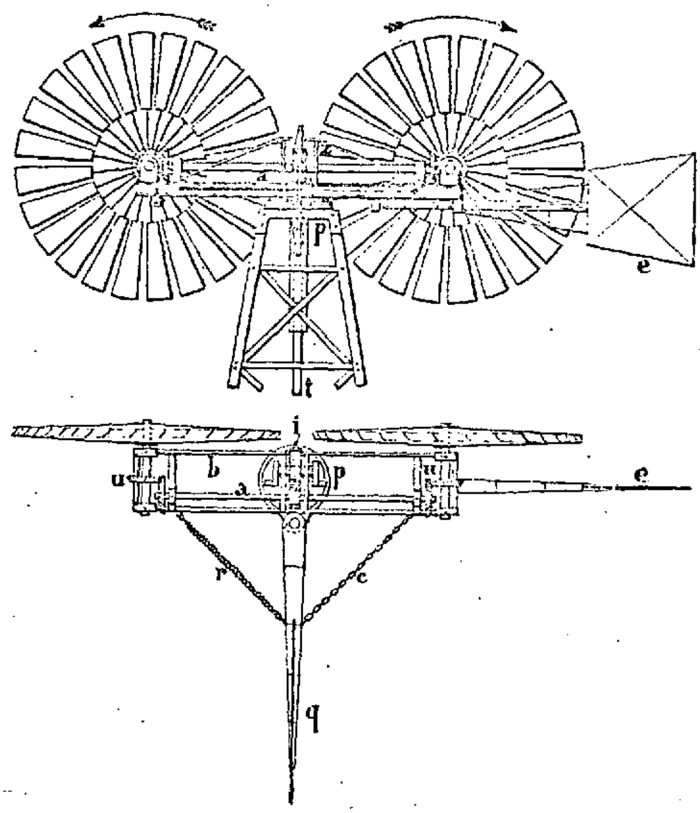

Fig. 36.   Twin wheels.

horizontal rotating shaft off-center in relation to the vertical orienting shaft. The entire drive assembly is mounted so as to pivot on a spindle ending in a large guyed column.

Subsequently, Bollée replaced the rudder with a small Delamolère flyer, a small-scale model of which is still in the National Conservatory of Arts and Crafts in Paris. The vertical shaft of the transmission was placed inside the column, and the method of elevating water, which initially consisted of a bucket-and-chain system, was replaced with a pump. A spiral staircase was installed around the column, making it possible to climb to a platform immediately beneath the governing and drive wheels, the orientation mechanism and the gearbox of the upper bevel gear.

Patent 167726 contains a drawing showing this final model and a funnel system placed around the periphery of the "governing" /65
wheel for the purpose of capturing a large quantity of air and thus increasing the speed and output of the windmill. The arrangement was completed by a semi-sphere on the hub. This drawing is

given in Fig. 37.

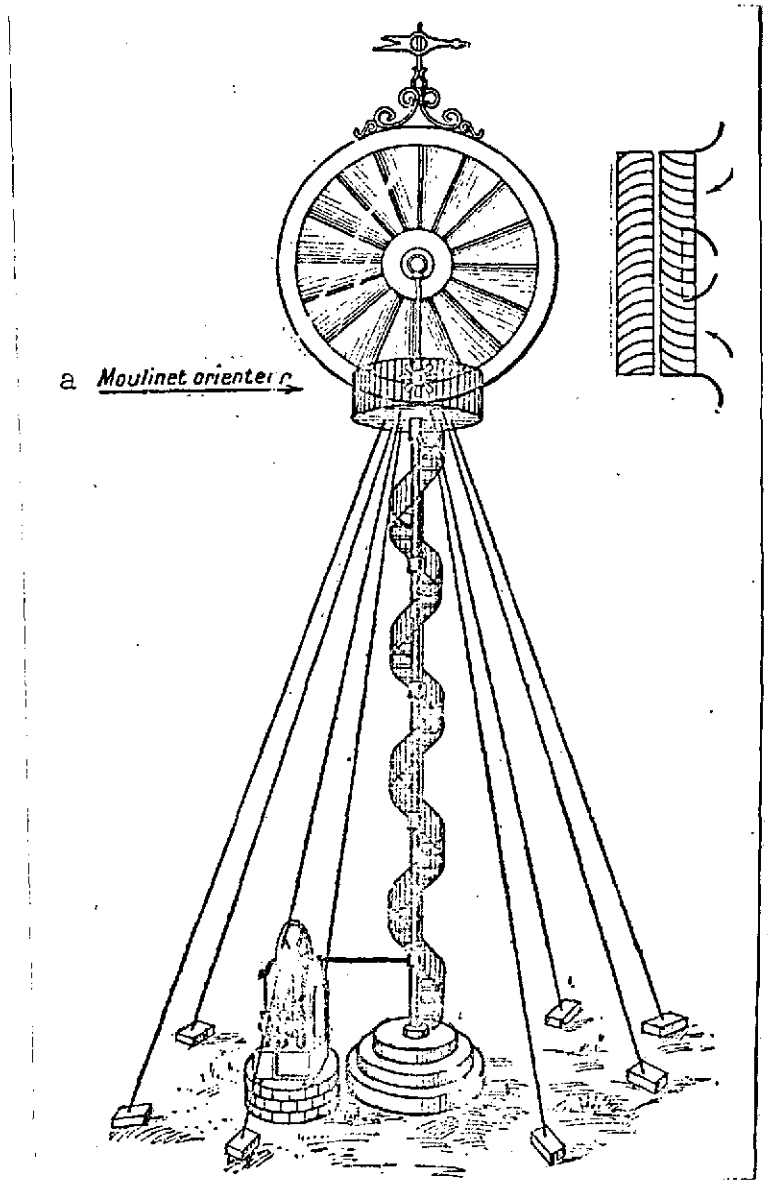

Fig. 37. First Bollée turbine, on a post with guy-wires.

Key: a. Flyer.

We believe that the word "éolienne" which Ernest Bollée used to describe his wind generators was originated by him. /66

The 1868 patent describes a wind generator with buckets and chain.

Currently the Société des Eoliennes Bollée [Bollée Wind Generator Company] is building four different-size models with respective diameters of 2.50 m, 3.50 m, 5 m and 7 m.

The movable wheel and the fixed wheel have a common framework consisting of a hub, extruded steel spokes and a sheet steel rim 2 mm thick. The vanes are secured on this rim by means of hot-bent angle irons strictly aligned with the profile of the vane. The vanes are connected to each other at their periphery by an external sheet steel rim 2 mm thick.

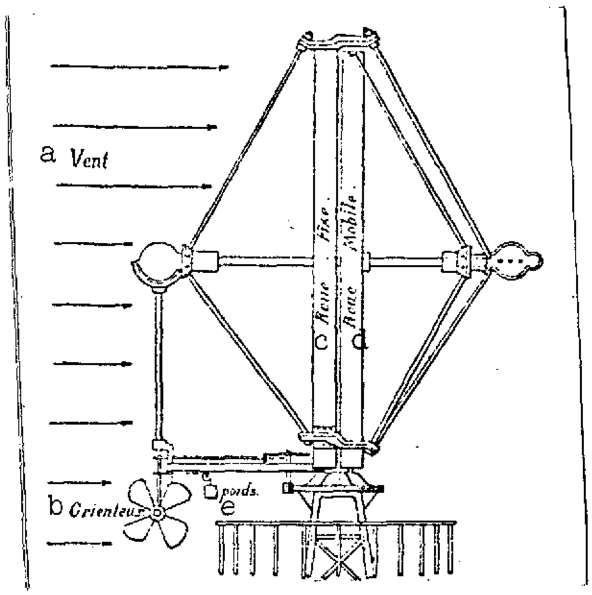

Fig. 38. Diagram of the Bollée turbine.

Key: a. Wind.
b. Orienting mechanism.
c. Fixed wheel.
d. Movable wheel.
e. Weight.

The fixed wheel and the movable wheel are bent on cast forms at a temperature of 400°; this temperature ensures that they will retain their curvature after cooling.

The movable wheel, which is very slightly offset from the axis of symmetry of the pylons is not overhung. Its shaft is attached to the center of the fixed wheel by a ball bearing, and is also secured by a second ball bearing of one piece with the system of guys which will be discussed below, mounted at its two extremities. This device /67 diminishes the fatigue of the machine under the effect of violent wind.

The fixed and movable wheel assembly is guyed so as to form a rigid triangular whole. Fig. 38 gives a schematic diagram of this guying system.

Orientation and Disorientation Mechanism

Automatic orientation and disorientation of our wind generators is provided by a specially designed swivel (Fig. 40). A wheel with blades b is normally oriented, by means of a counterweight D, in a plane perpendicular to that of the fixed and movable wheels. This wheel with blades, rotating on a horizontal shaft, is of one piece with a frame f which is able to turn on a vertical axis. The wheel is thus able to perform two rotational movements,

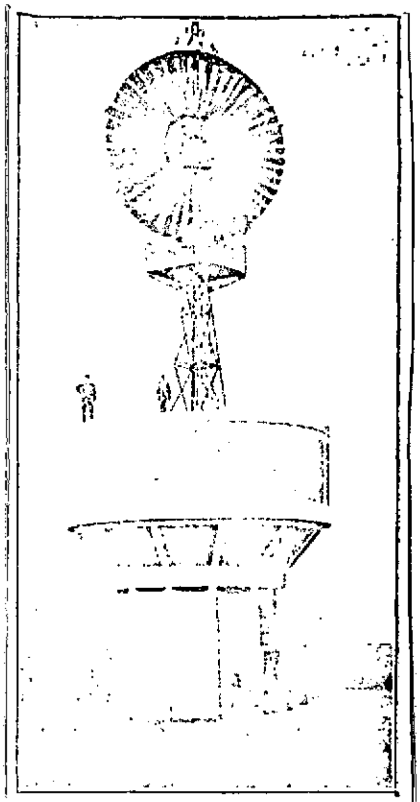

Fig. 39. Bollée turbine on concrete tank.

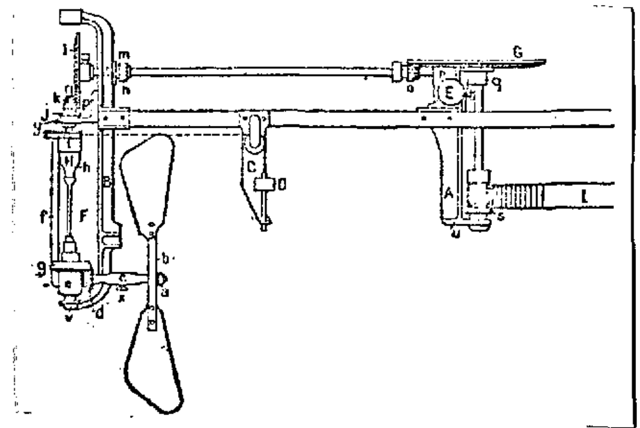

Fig. 40. Details of the Bollée orientation mechanism.

around a horizontal shaft and around a vertical shaft, which are sufficient to orient the assembly and turn it aside in excessive winds. During orientation, the bladed wheel functions /68 as an ordinary wind rose on a toothed ring I secured on the pylon. If the wind speed exceeds 12 m/sec, the bladed wheel and its frame are able rotate 90° on their vertical shaft, this rotational movement being limited by a stop which places them in a position parallel to the wheels of the wind generator. This movement swivels the fixed and movable wheels into the plane of wind, thus turning aside from its direct thrust. As soon as the storm wind has stopped, the counterweight D returns the bladed wheel to its position in the wind.

A lever mechanism makes it possible to activate the counterweight D to return the wind generator to its position in the wind from the base of the pylon by means of a cable and winch.

The swivel assembly is mounted on ball bearings. The cast pinions are contained in gearboxes with oil baths.

The transmission consists of a rotating vertical shaft.

We asked the Société des Eoliennes Bollée if their system using a fixed governing wheel improved the efficiency of the wind generator. They stated that the ratio between the effective wind power computed by the formula $\frac{dSV^3}{2g}$ and the power represented by the weight of the water actually elevated to a tank by the pump is approximately 40%. This net efficiency includes that of the wind turbine, that of the vertical transmission and its two pairs of bevel gears, that of the pumps and their control mechanisms, and the loss of head in the piping.

If this is indeed the case, it provides sufficient proof of the value of the improvement obtained by adding a governing wheel. (See Chapter X.)

The Use of American Windmills in Tunisia

Mr. Gagey, a teacher at the Colonial School of Agriculture in Tunis, has written an interesting article which has appeared in Le Bulletin de la Direction de l'Agriculture et du Commerce [Bulletin of the Administration of Agriculture and Commerce] for January 1904 on the use of windmills in Tunisia. The following discussion has been extracted from this article.

Tests. At the School of Agriculture, we have made a few tests on the Aermotor 4.20 m in diameter, mounted on a 21-meter pylon, produced by Mr. Leclerq of Tunis. However, lack of an anemometer prevented us from checking the above formula, since it was impossible to determine the exact speed of the wind at this height. These tests are to be performed this year, since currently there are few statistics available on windmills, and it is necessary to /69 obtain precise data in this area in order to make a well-founded choice of assembly.

The tests were performed with either a Prony brake or the Ringelmann automatic grip and release brake.

Jan. 19, 1903. Wind estimated at approximately 7 or 8 m/sec:

Rate of Operation of Pulley		Effective Power with Brake
With	282 rpm	60.46 kg
Prony	244 rpm	63.46 kg
brake	228 rpm	70.36 kg

May 26, 1903. With Ringelmann brake. Rate of operation of pulley: 444 rpm; effective power with brake: 74.41 kg, or close to 1 hp.

June 1, 1903. Light storm winds:

	Load with Brake	Number of Rotations of Pulley	Effective Power with Brake
With Ringelmann brake	4 kg	472 rpm 452 rpm	131.8 kgm 63.8 kgm = 0.8 hp
	5 kg	366 rpm 544 rpm	127.75 kgm 189.88 kgm = 2.5 hp

Overall average: 128.2 kgm = 1.7 hp.

The tests on June 1 were performed from 4:00 to 5:00. It may be seen that in one hour the minimum power was 0.8 hp and the maximum 2.5 hp, which shows the wide irregularity of the work furnished, due to variations in wind speed.

This also shows that tests on windmills are fairly problematic, since only daily, monthly and annual averages can be tabulated. A test with the brake applied, performed once by chance, will be of no value. For the proper study of a windmill it would be necessary to use a recording anemometer and a recording brake in order to establish accurate averages.

From the June 1 tests, it appears that a 4.20-meter windmill would be able to supply barely 2.5 hp under light storm winds.

June 23, 1903. Approximate wind speed: 7 m/sec.

/70

	Load	No. of Rotations of Pulley	Effective Power with Brake
With Prony Brake	7 kg	384 rpm	53.86 kgm
	9 kg	252 366	45.11 kgm 65.51 kgm

Test average: 54.82 kgm = 0.73 hp.

Through a cable and intermediate mechanism, the Aermotor of the School of Agriculture drives a siphon-pump 89 mm in diameter which elevates water to a total height of 11.70 m. The suction height is thus 2 m.

The speed reduction with the pump is $\frac{1}{15.7}$.

The final toothed wheel which attacks the piston rod makes it possible to obtain four different lengths of stroke for this rod, i.e., 15 cm, 24 cm, 31 cm and 35 cm. Our pump operates with a 24-cm stroke.

The theoretical volume of a cylinder is thus;

$$\pi R^2 H = 3.14 \times 0.0445^2 \times 0.24 = 1.4921 \text{ liter}$$

The average of an extremely large number of pump strokes was found to be 1.47 liter, and in fact the volume of water elevated by piston pumps is actually known to be slightly less than the theoretical volume of the cylinder.

May 30, 1903. The pump operated at 25 strokes per minute, which corresponded to 390 rotations of the base gearshaft, or 65 rotations of the windmill wheel.

Thus the flow rate per hour would be:

$$1.47 \ \ell \times 25 \times 60 = 2.205 \ m^3$$

With a satisfactory wind this flow rate can be increased by adjusting the pump to the long 35 cm stroke, which would result in approximately 3.8 m^3/h.

There are still highly significant tests to be performed along these lines. Ginestous has performed these calculations, from a theoretical standpoint, in the Revue tunisienne de l'Institut de Carthage [Tunisian Journal of the Institute of Carthage], (No. 36, October 1902).

The main shaft of the Aermotor of the School of Agriculture drives a crushing mill with cast grindstones.

We have operated this mill with different types of grain. /71
It is able to produce flour, like our mills with stone grindstones or like the Schweitzer windmill; it is able to produce semolina, which is used by the Arabs, and is able to crush wheat, barley and oats. It is therefore a useful farm tool, since it is able to use a natural force to prepare animal provender. In addition, when it is not otherwise in use, it could be used by the farmer to do his grinding at low cost. However, windmills are known to require a great deal of energy, and thus a fairly high wind will be necessary for operation. Nevertheless it would still be possible to perform "Arabian" grinding, the work requiring the greatest amount of power; it would merely be necessary to perform the operation several times, making successive passes to grind the flour to increasing fineness.

Jan. 5, 1903. Low wind. We made semolina from hard wheat by performing five successive passes.

Pass	Length in Sec	Speed of Grindstones in rpm
1	55	150
2	60	172
3	120	84
4	120	156
5	125	144

June 8. Again, semolina was made from 10 kg of hard wheat in four successive passes.

Pass	Length in Sec	Speed of Grindstones in rpm
1	6	140
2	12	152
3	11	80
4	14	70

The product was passed through an Arabian screen and the yield was as follows:

From 10 kg hard wheat: Bran............1.730 kg
Semolina........7.670 kg

Counting the time of transfer to the hopper, therefore, 7.600 kg semolina were produced in approximately one hour.

June 22. The wind was fairly high to make only a single pass. Arabian grinding was performed on 20 kg hard wheat for 8 min 42 sec, for a rate of 137 kg/h. The average speed of the grindstones was 214 rpm.

15 kg oats were crushed in 8 min 5 sec, for a rate of 111 kg/h, with the grindstones operating at 273 rpm. The operation is performed very smoothly, without noise. /72

Finally, 15 kg barley were crushed for 6 min 10 sec, or a rate of 145 kg/h, with the grindstones at 349 rpm. Here it was necessary to have a somewhat higher wind, estimated at approximately 10 m/sec.

The above figures show that, with sufficient wind, the windmill is able to crush at least 100 kg/h of material. It could thus be extremely useful, even on a farm with a large number of cattle.

In America, the ideal country for windmills, a few experiments have been performed and have yielded highly attractive results. These were the experiments of Prof. Murphy on the output of windmills and those of Prof. King on grinding performed by the same windmills.

Experiments of Prof. Murphy

A translation of the experiments of Prof. E. C. Murphy, a government hydrographical engineer in Lawrence, Kansas, has appeared in the Bulletin de la Société d'encouragement pour l'industrie nationale [Bulletingof the Association for the Encouragement of National Industry] (No. 4, April 1898). A summary based on the report in this Bulletin will be given below.

This investigator worked with 27 windmills of different types and sizes.

If one compares windmills with the same diameter (2.45 m), all driving pumps whose dimensions, although they may vary, combined with the height of elevation, are such that the useful work per pump stroke is the same (11 to 13 kgm), one finds:

	Minimum Wind Speed for Starting Windmill
Aermotor	3.40 m/sec
Idéal	4 m/sec
Gem	4.50 m/sec

	Maximum Power Reached at a Speed of:
Aermotor	133m/sec
Idéal	8.80 m/sec
Gem	13 m/sec

This maximum power was: Gem: 1 hp
Idéal: 1.8 hp
Aermotor: 2 hp

At a speed of 8.80 rpm, however, the Idéal assembly reached the maximum power of 1.8, as opposed to 1.7 for the Aermotor. /73

This finding shows that under high winds the output curve of the Idéal assembly drops more rapidly than that of the Aermotor, which, on the other hand, undergoes a constant increase. Thus high winds are more efficiently used by the Aermotor. Nevertheless it may be noted that this curve for a windmill can very easily be changed. One need only slow down the vanessystem by stretching its spring by means of the adjusting nut.

A comparison of two 3.60-meter windmills, the Aermotor and the Gem, both driving a pump under conditions such that the useful work per pump stroke is the same (62 to 63 kgm) shows the following:

	Effective Power in Horsepower at Wind Speeds of:		
	7 m/sec	8.80 m/sec	11 m/sec
Aermotor: Reduction 3 1/3	0.137	0.16	0.19
Gem: Reduction 2	0.100	0.12	0.14

It may be seen that the windmill with the highest reduction is more efficient. This is because the vanes will undergo a greater number of rotations for a single pump stroke and the assembly is able to overcome its load more easily and generally will start better under low winds.

If a windmill is heavily loaded it will operate only in high winds; if its load is slight it will start more easily under a light breeze.

Depending on whether the country involved has predominantly strong winds or predominantly light winds, therefore, it will be to advantage to give the windmill a heavy or an extremely light load in order to obtain the maximum quantity of water per year. This would be true in the cases of regular and continuous water supply, for a farm or a home, for example.

On the other hand, if irrigation is being performed at set times, it is necessary to know the wind system at these times and to load the windmill accordingly so as to obtain the maximum amount of water during that period. Data on average monthly windspeeds are thus extremely useful for selecting an appropriate pump stroke.

We had previously seen that a siphon-pump 89 mm in diameter, for example, could have four different strokes: 15 cm, 24 cm, 31 cm and 35 cm.

Thus one need only change this stroke every month by moving the rod on the large gear wheel, depending on the average monthly wind speed. /74

However, the wind speed will vary widely during a single month and even during a single day. For maximum efficiency, it would therefore be preferable to vary the stroke automatically. (See the description of the Hérisson mechanism in Chapter VIII on transmission systems.)

From the experiments of Prof. Murphy one can derive the following data on the effective power of windmills, measured with the Prony brake.

	Load of Brake in kg	Effective Power in hp for Wind Speeds per second of:					
		3.60 m	5.30 m	7 m	8.80 m	11 m	13 m
Perkins, diam. 4.25 m	2.7	0	0	0.313	0.609	0.937	0
Aermotor, diam. 3.60 m	2.7	0	0	0	1.027	1.451	1.576
	1.8	0	0.403	0.553	0.653	1.020	1.086
	0.91	0.089	0.285	0.386	0.458	0.523	0.540
	0.70	0.050	0.073	0.087	0.111	0.128	0.151

This table shows:

(1) That given an equal wind speed and brake load, the Aermotor, although of smaller diameter, is more powerful than the Perkins assembly.

(2) That under strong winds a 3.60-meter windmill will produce approximately 1.5 hp.

(3) That at equal wind speeds the power increases with the load -- up to a given limit, obviously.

Thus when it is possible to use the Hérisson device, one obtains the advantage of enabling the windmill to operate at maximum load, as in the case of reciprocating engines, for example.

Furthermore, the Murphy experiments show that the more the load of the windmill is increased, the less its speed decreases. Thus any increase in load beyond a given minimum is translated into /75 a barely perceptible loss in speed, but one which is valuable for the efficiency of the assembly.

Experiments of Prof. King

Prof. F. A. King of the University of Wisconsin has compared the grinding of different types of grain by a gas engine and by a windmill, using a windmill with cast grindstones of the Aermotor type.

Here we will give only the data relative to the practical work, that is, those relative to the weight of the ground wheat and oats produced by a windmill.

Table 1 gives the amount of wheat ground into flour for baking per hour, with the percentage for each screening. This work was performed by an Aermotor 3.60 m in diameter.

Screen No. 1 had eight openings per inch.

Screen No. 2 had ten openings per inch.

Screen No. 3 had 16 openings per inch.

Screen No. 4 was the finest screen.

TABLE 1

Wind Speed in m/sec	Weight of Flour Processed per Hour	Degree of Fineness in % Material By Screen No.			
		1	2	3	4
3.1	5 kg	5.4%	13.4%	46.1%	35.1%
4.4	79 kg	7.0%	17.3%	44.2%	31.5%
6.6	107 kg	8.0%	5.3%	47.0%	46.9%
8.8	306 kg	7.0%	17.3%	44.2%	31.5%
11	323 kg	1.2%	3.3%	35.8%	59.7%

The percentage furnished with each screen explains, for example, the relative lack of difference between the product processed at a wind speed of 8.8 m/sec and one of 11 m/sec. In the latter case, the quantity of flour No. 4 was extremely high (60%), requiring considerable work by the windmill.

Table 2 shows the output of a flour mill with the trademark "N" and an Aermotor 4.80 m in diameter.

TABLE 2

Wind Speed in m/sec	Weight of Flour Processed per Hour	Degree of Fineness in % Material, By Screen Number				
		1	2	3	4	/76
Wheat:						
4.80	48 kg	3.3%	3.4%	24.3%	69%	
7	136 kg	10.1%	15.7%	15.7%	34.9%	
10	224	4.7%	10.4%	43.7%	41.2%	
Oats:						
5.70	37 kg	22.2%	10.7%	36.8%	30.3%	
12	140 kg	17.7%	13%	37.6%	31.7%	

Conclusions

The preceding discussion shows that on the whole, there is little information currently available on windmill output.

Use of the Coulomb equation for a given wind speed does not produce results in absolute agreement with those furnished by the brake, which are completely accurate.

Ringelmann gives a slightly different equation:

In kilogram-meters: $T = 0.0795\ S\ v^3\ k$

In horsepower: $T = 0.00106\ S\ v^3\ k$

And for k = 20 to 4

Finally, Mr. Mulotte, Superintendent of Bridges and Causeways, has derived the following very simple equation from German publications:

In horsepower: $T = \frac{D^2 3V}{3,600}$

D being the diameter of the vanes. The results given by this equation also seem to be too high.

New tests with the use of brakes will therefore be necessary, with corresponding wind speed measurements by means of an anemometer placed at the same height as the windmill, and it will be necessary to derive a practical equation from these tests which will make it possible to determine the diameter of the windmill to be used to obtain a given output, at a given location and consequently at a known average wind speed.

As a followup to the above article by Prof. Gagey, the reader may want to consult the numerous tables given below, in Chapter X on the drawing of water and Chapter XI on the production of electricity.

CHAPTER 4. WIND MOTORS WITH FOUR TO EIGHT BLADES /77

Wind Motors with Thick Blades

The Agricco and Aurora companies of Denmark and the Adler Company of Germany use wheels with four, six, seven or eight vanes, fish-shaped in cross section as shown in Fig. 41.

Tests to determine optimum profiles for aircraft wings have shown that a wing with a fish-shaped cross section will not produce significant eddies as it moves in the air.

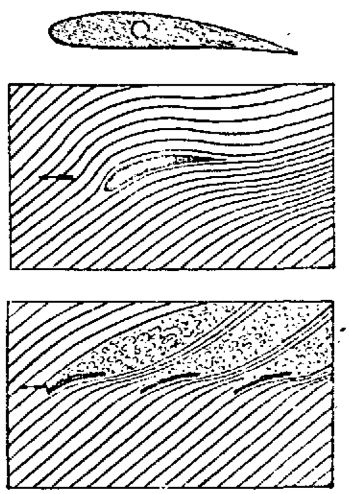

Fig. 41.

Fig. 42.

Fig. 43.

Fig. 41-43. Fish-shaped cross sections of wings or vanes.

The drawings in Figs. 42 and 43, prepared by the Adler Company, show the differences in the eddies generated by a thick vane and by sheet metal vanes with a given downward curvature.

Fig. 44 shows an Agricco wind motor with four vanes a, which are /78
able to pivot on a shaft when the wind becomes too violent. The assembly is oriented to the wind by a small paddle wheel which comes into operation when the direction of the wind ceases to be perpendicular to the plane of the drive wheel.

Fig. 45 shows an Adler wind motor with rotating vertical shaft transmission. The wheel has six, seven or eight vanes, depending on its diameter; the assembly is oriented by a rudder, and turned aside from the wind by a fixed aileron in the plane of the drive wheel.

Fig. 118 shows the Aurora wind motor with four thick vanes, powering a generator installed at the top of the pylon. The assembly is oriented by a rudder and turned aside from the wind by having the axle of the wheel off-center from the axis of the pylon.

The Conical Soerensen Wind Motor (Fig. 46) /79

Built by O. Roosen Runge in Neurmühlen close to Kiel, Germany, this assembly is characterized by its axis inclined 15° toward the horizon and six vanes inclined 75° toward the main shaft.

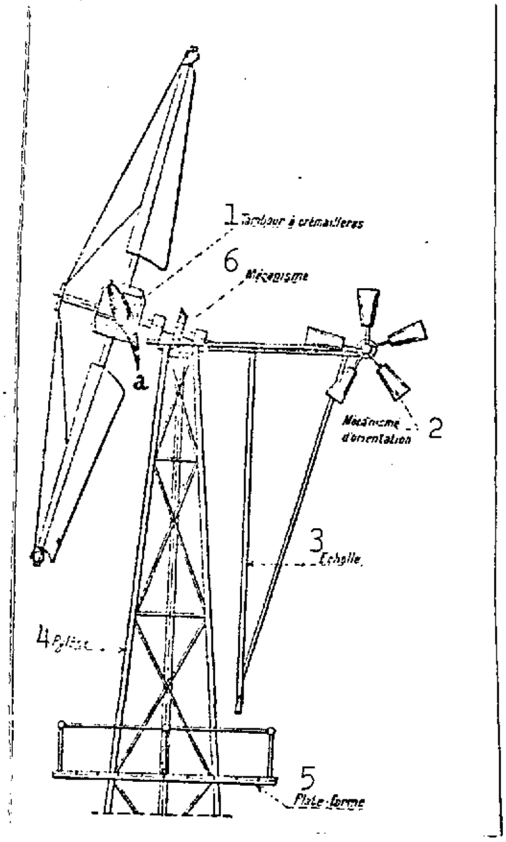

Fig. 44. Agricco wind motor.

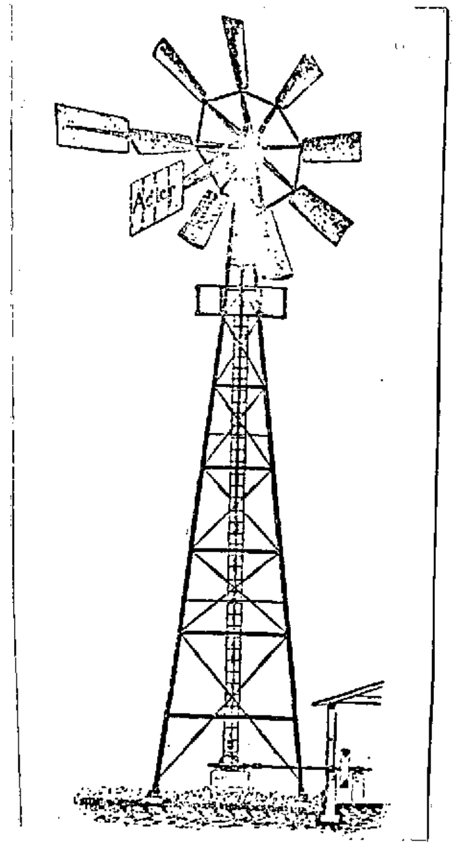

Fig. 45. Adler wind motor.

Key: 1. Rack drum.
2. Orientation mechanism.
3. Ladder.
4. Pylon.
5. Platform.
6. Mechanical parts.

The vanes are bent and incurvated, a configuration which guides the air currents from the convexity close to the hub to the concavity toward the tips of the vanes, whose ends are spoon-shaped. This shape for the wheel would increase the power, which with equal surface area would be 2 1/2 times that of the American turbine. The vanes consist of elements tilting on shafts perpendicular to the axis of the vane, along the lines of the Danish Mammouth windmills.

Orientation is performed by two auxiliary turbines (wind roses); a basic diagram of the entire assembly is shown in Fig. 46. These devices take into account the principles demonstrated by practical experience which we have described above.

Here, according to Hütte, are the outputs attained by the Soerensen windmills at wind speeds of 7 m/sec.

Diameter of Wheel in meters	3.8	5.4	6.6	7.6	8.5	9.3	10.1	10.8	12	13.2	14.7	17	19
Output in hp in a 7 m/sec wind	1	2	3	4	5	6	7	8	10	12	15	20	25

(Diameter)	22.5	24	26.85
(Output)	35	40	50

Due to the conical shape of the wheel it is possible to give it it quite large dimensions.

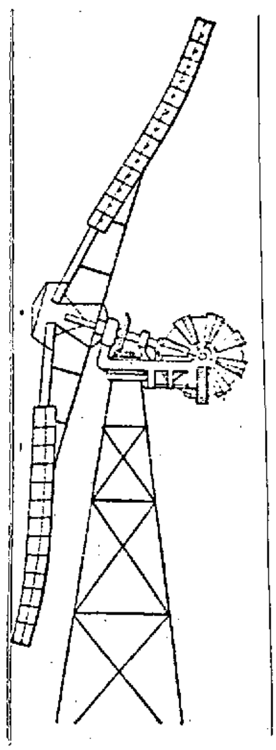

Fig. 46. Soerensen wind motor.

These windmills are able to start in 2 m/sec winds to drive pumps and 3 m/sec winds for generators. Satisfactory efficiency is obtained at wind speeds of 4 to 6 m/sec.

Mammouth Wind Motors

These assemblies, which are designed

[Pages 80 and 81 missing in original.] /X

blades are wooden and which function by means of a perpetual screw (RT) and a shaft U on a toothed ring at the base of the head V of the wind motor. /82

A mechanism consisting of a lever with counterweight (KKL), a rod concentric to the main shaft (II) and reverse levers and rods (JG) makes it possible to vary the angle of the vane elements F and to stop the wind wheel from the base of the pylon.

The gear mechanism is contained in an impervious gearbox with oil bath (ON); its energy is transmitted to the ground by a rotating vertical shaft.

Fig. 49 shows classical Dutch windmills converted to the use of Mammouth vanes.

The following tables give the characteristics of the Mammouth wind motors, which are widely used in Denmark.

<u>Danish Mammouth Four-Vane Wind Motors</u>

POWER IN HORSEPOWER

a DIAMÈTRES des ailes.	b VITESSES DU VENT PAR SECONDE							
	5	6	7	8	9	10	11	11,4 plus.
7	0.9	1.5	2,4	3.5	4.6	5.5	6.3	6.9
9	1.65	2.9	4.6	6.85	8.6	10,0	11.0	12.5
10	1.8	3.1	5.0	7.1	9.2	11.1	13,0	14.4
12	2.6	4.5	7.6	10 2	13.2	16.0	18,9	20.0
14	3.5	6.2	9.7	14.4	18.0	22,0	25,8	28.5
16	4.6	8,0	12.6	18.2	23.4	28,5	33,5	37.0
18	5.8	10.0	16.0	23.0	29.7	35.0	42.4	47.0

Key: a. Diameters of vanes.
b. Wind speeds per sec.

CHARACTERISTICS OF DANISH MAMMOUTH WINDMILLS FOR PRODUCTION OF ELECTRICITY OR PUMPING OF WATER

Diameter of Wheel:	10 m	12 m	14 m	16 m	18 m
Length of vanes	3.75 m	4.50 m	5.25 m	6.00 m	6.75 m
Width of vanes	1.25 m	1.50 m	1.75 m	2.00 m	2.25 m
Total area in m^2	18.75	27.00	36.75 m	48.00 m	60.75 m
Number of shutters	32	36	44	52	60
Weight of windmill:					
Gross	2,100 kg	2,425 kg	3,075 kg	5,100 kg	6,900 kg
Net	2,000 kg	2,250 kg	2,920 kg	4,900 kg	6,700 kg
Weight of gearbox	450 kg	450 kg	800 kg	800 kg	600 kg
Weight of lower gears	85 kg	85 kg	175 kg	175 kg	225 kg
Capacity of generator (max.) in kW	10.5	13.5	19.5	25.5	30
Stroke of rod in mm	310	370	430	490	540
No. of rotations: V					
V = 6 m/sec	65	54	45	40	36
V = 12 m/sec	130	108	90	80	72
No. of piston strokes per minute	29	24	20	18	16
Weight of 15 to 20 m pylon, per meter, in kg	100	130	1160	165	195

CHAPTER 5. WIND MOTORS WITH TWO, THREE AND FOUR HELICOIDAL BLADES /84

Wind Motors with Two Blades (Research communicated by Mr. Constantin, Engineer and Constructor)

Mr. Constantin, who has been responsible for the development of some quite remarkable aircraft stabilizers and propeller improvements, recommends the use of two-blade airscrews, which offer better efficiency than wheels with a number of small blades. He has been kind enough to provide us with the following information in this regard.[1]

The best-suited assembly available today to convert the kinetic energy of wind into usable mechanical energy is the two-blade wind turbine. This fact can no longer be debated after the research of Lapresle at the Eiffel Laboratory.

The use of two blades offers the following advantages:

(1) Greater power.

(2) Higher aerodynamic efficiency, that is, less thrust.

(3) A higher rotation speed, that is, a mechanical transmission system of lower weight.

(4) Lower cost price.

The only disadvantage of this type of turbine -- a very slight disadvantage under the circumstances -- is its low starting torque. Later on we will see how easily and conveniently this can be cancelled.

Under given use conditions which are easily obtainable, the outputs of these turbines reach values which may be determined by the following equation:

$$P = 0.000267\ a\ V^3\ D^2$$

in which P is the mechanical power expressed in horsepower;

a is the ratio of the density of the air whose kinetic energy is being used to that of the air in the laboratory (15°C and 760 mm Hg); /85

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[1]This text and the accompanying drawings appeared in the journal La Nature.

V is the wind speed in m/sec;

and D is the diameter of the turbine in m.

This equation would undoubtedly be applicable to laboratory tests on turbines with a diameter of 0.80 m at the most. However, in aerodynamics the unexpected often produces fortunate results: for reasons involving the air viscosity, the results have a sharp tendency to improve in the change from a small to a large model. Furthermore, we were in fact able to observe this tendency in practical tests on the ship Le Bois-Rosé, which was equipped with a two-blade turbine 9 m in diameter (see Chapter 13).

It was quite encouraging to obtain an output from a turbine 9 m in diameter which was very close to the output we had computed earlier, and tended to be above rather than below the theoretical value. On this basis there would be no risk in applying the same calculations to turbines 30 and 40 m in diameter, since these dimensions are ones which we can safely consider today without prejudging future developments. I will explain why later on.

At the summit of Mt. Ventoux, at an altitude of 1900 m, where the air density is only 83% that at sea level, turbines of this type would perform as follows:

At a Wind Speed of:	Turbine 30 m in Diam.	Turbine 40 m in Diam.
6 m/sec	43 hp	76.5 hp
10 m/sec	200 hp	356 hp
14 m/sec	546 hp	972 hp
21 m/sec	1,840 hp	3,275 hp

An analysis of the meteorological conditions at Mt. Ventoux during the year 1913, a year for which we have complete data, shows that there were:

106 days of approximately 10 m/sec wind
63 days of approximately 14 m/sec wind
50 days of approximately 21 m/sec wind

On the basis of these 219 days alone, it is easy to calculate that /86
the first turbine would have been able to supply the same amount of energy as if it had had a continuous output of 400 hp for 365 24-hour days.

Under the same conditions, a turbine 40 m in diameter would have been able to generate power equivalent to a continuous output of 710 hp.

With a diameter of 50 m, the power increases to approximately 1,110 hp.

Now, there is room on Mt. Ventoux for a large number of units of this type...

Analysis of Wind Turbines from the Standpoint of Strength of Materials

But would such assemblies be able to withstand the stresses to which they would be subjected? This is the first objection which must be expected; in the following discussion I will try to answer it a priori.

(a) Centrifugal stresses. An analysis of the centrifugal stresses exerted on airscrew or turbine blades quickly reveals that the most important factor to be considered is not the radius R or the angular speed ω, but the product $R^2\omega^2$, which represents the square of the peripheral speed.

Moreover, the above-mentioned research performed at the Eiffel Laboratory has shown that in order for a two-blade wind turbine to furnish the maximum output compatible with its diameter, its peripheral speed must be slightly less than six times the wind speed.

Thus if devices are provided to turn the assembly aside when the wind speed reaches 25 m/sec, the peripheral speed of the blades will never exceed 6 x 25 = 150 m/sec.

Setting aside the values obtained by Rateau and Maurice Leblanc in certain applications, the usual peripheral speed of aircraft propellers may be set at 300 m/sec. Other things being equal, therefore, the centrifugal stresses occurring in the turbines under consideration -- for any given diameter -- will never be more than 1/4 the corresponding stresses undergone by aircraft propellers.

To remove any doubt in this regard, one can directly compute the stress at the blade insertion -- which is assumed to pass through the axis of rotation -- due to centrifugal force in two simple cases: a cylindrical blade and a conical blade.

The results of these calculations are given by the following /87
two equations:

$$T_1 = \frac{\delta}{g}\frac{R^2 \omega^2}{2}$$

$$T_2 = \frac{\delta}{g}\frac{R^2 \omega^2}{12}$$

in which:

T_1 and T_2 are the stresses corresponding to the two cases under consideration;

δ the density of the material used;

g the acceleration of gravity.

For steel with a density of 7.8, one obtains:

$$T_1 = 10 \text{ kg/mm}^2$$

$$T_2 = 1.6 \text{ kg/mm}^2$$

No matter what design is ultimately selected, it can always be made such that the real stress due to centrifugal force falls between these two values, which makes it possible to retain an extremely high safety coefficient while at the same time using malleable steel and thus obtaining an extremely low cost price.

The blades will of course be subjected to other stresses, first of all bending stresses.

(b) Bending stresses. This type of stress arises from the thrust of the wind, and, as with aircraft propellers, the corresponding moment reaches a fairly high level. However, here the conditions are much more favorable.

In the first place, it is possible to extend the rotational shaft forward and to guy the blades.

There are other, still greater advantages. In aircraft, design, the neutral axis of the blade is arranged in such a way that the bending stresses are balanced by a component of the centrifugal force. Unfortunately, this type of compensation holds only at a given altitude, due to the concomitant variations in air density, and thus the judicious placement of the neutral axis is only a palliative measure. The altitude of the wind turbines under consideration here is constant, however, and thus perfect compensation may be a practical possibility.

(c) Stiffness of blades. Naturally the blades must be able to support their own weight at rest, no matter what their position, without sagging or buckling. There need be little concern in this regard, however, considering that a blade 20 m long, for example, could have an average width[2] of more than 3 m and a thickness of more than 0.50 m on the leading edge 1/3 away from the hub. One can see that the moments of inertia which may be expected in a blade of this size will be quite adequate. /88

Support Pylons

If, as we assumed above, the turbine is equipped with deflection mechanisms which come into operation at a wind speed of 25 m/sec, the maximum power collected on Mt. Ventoux by a unit 40 m in diameter would be approximately 5500 hp.

The corresponding thrust, for an aerodynamic efficiency of 50%, would thus be approximately 33 tons. To this figure should be added the weight of the pylon itself and possibly that of the transmission system. Since there are no limitations on the dimensions of the seatings and the component parts of the pylon, no special problems may be expected in obtaining the desired strength.

Conversion of the Mechanical Energy Collected into Immediately Usable Energy

Once the conversion of the kinetic energy of the wind into mechanical energy (mechanical in the industrial sense of the word) has been assured, this energy must be converted a second time to make it simultaneously easy to distribute and immediately usable; in other words, it must be converted into electrical energy.

In the tests made in this area so far, the windmill has always driven the generator by means of a transmission system (gear trains, shafts with universal joints, cables, belts, etc.). We could certainly do the same, using gear trains of the same type as those used for rolling mills, but it would undoubtedly be much more efficient to connect the turbine directly to the generator by enclosing the latter, with its accessories and distribution panels, in a structure with a low lead resistance which can be swiveled on a vertical shaft to move the assembly.

[2] The width of the blades on the Constantin airscrews is equal to approximately 1/6 their length between the hub and the tip.

The rotation speeds for wind speeds ranging from 10 m/sec to 25 m/sec would fall between 36.5 and 95 rpm for the first turbine and 28.5 and 71.5 rpm for the turbine 40 m in diameter. These speeds are quite acceptable given the outputs involved. /89

In addition, the presence of these structures to the right of the hub of the turbine would facilitate the flow of air and would undoubtedly increase the aerodynamic efficiency of the system.

The operating speed margins indicated above draw attention to one of the most difficult problems confronting engineers in tests on the use of the kinetic energy of wind. The power produced by wind turbines, if certain use conditions are maintained, is proportional to the third power of the wind speed; in other words, it varies over a wide range. The following discussion will consider these variations briefly and show how their drawbacks can be prevented.

(a) Instantaneous variations. These are low-amplitude variations which are produced continually. It is obvious that their effect on an assembly with heavy inertia, and all the more on several connected assemblies, will be negligible.

(b) Slow variations. These are variations which occur from one day to the next, for example. Due to their occurrence, the energy must be used either by industries with an extremely flexible level of operation, or, better still, in conjunction with other backup energy sources.

In all cases, these variations must be followed at the receiving station by the connection or disconnection of as many energy-consuming units as necessary. Since wind power will undoubtedly be the least costly form of energy, making it advantageous to use it as often as possible, a system of this type will be the natural choice.

(c) Fast variations. These are variations occurring every 15 min, for example.

In most current installations a storage battery is used to absorb these variations.

However, for an installation of the output considered, the use of a storage battery presents a number of drawbacks which appear to be prohibitive.

This is not the case with an electric boiler with steam accumulator, and it would even be possible to design an installation in which all the mechanical energy drawn from the atmosphere

and converted into electrical energy would be used for the production of pressurized steam by means of ac or dc boilers. It /90
would not be necessary to maintain a constant frequency, since the power factor in electrode and alternating current electric boilers is very close to unity. This pressurized steam would be used in turn, either directly for certain industries (dye works, sugar refineries, paper mills, etc.) or by reconversion into electrical energy which now would be suited for home use.

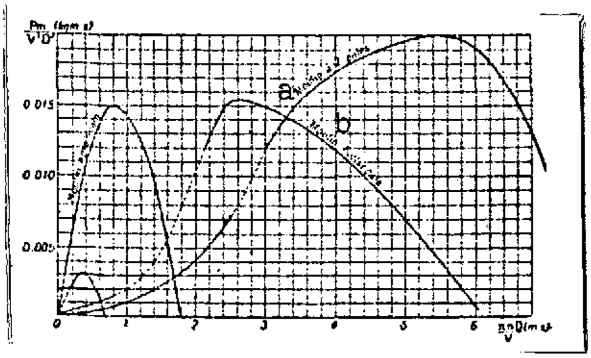

Fig. 51. General results of the Eiffel Laboratory tests on windmill output. The power coefficients shown, which are expressed in kilogram-meters per second, are given as a function of the ratio of the peripheral speed of the windmill to the wind speed. The advantages of a two-blade windmill or turbine from the standpoint of power and rotation speed are quite obvious.

Key: a. Two-blade windmill.
b. [Word illegible] windmill.

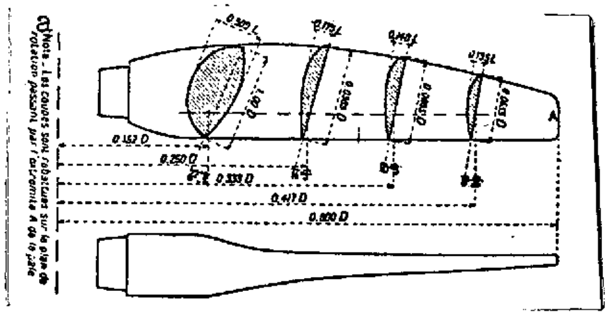

Fig. 52. Sketch of a wind turbine blade tested by Constantin in the Eiffel Laboratory. The results of the tests on this model are given by the diagram in Fig. 54.

Key: a. Note: The cross sections are projected onto the plane of rotation passing through the tip A of the blade.

There can be no doubt that this would be a profitable system from an economic standpoint, since we know that 4 kWh used in an electric boiler will yield approximately as much steam at the same pressure as one kilogram of coal at 7,000 calories.

Thus the assembly 40 m in diameter considered above could /91
save 800 to 900 tons of coal a year, which represents a considerable financial saving.

Large advances have been made in electric boilers over the past few years, and technical journals have recently published descriptions of an 18,000 kW unit installed in Niagara in the U.S., which has been found completely satisfactory. In addition, French constructors have already obtained significant results along these lines.

It would not be presumptuous, therefore, to expect widespread use of this type of energy converter in the future.

However, it is almost certain that electric boilers could be used only as a buffer, and a very large part of the energy produced and suitably converted would have to be transmitted directly to interconnected networks.

Orientation Mechanism Developed by Constantin

The rudder has two curved surfaces with vertical axes facing each other on their concave sides, as shown in Fig. 56.

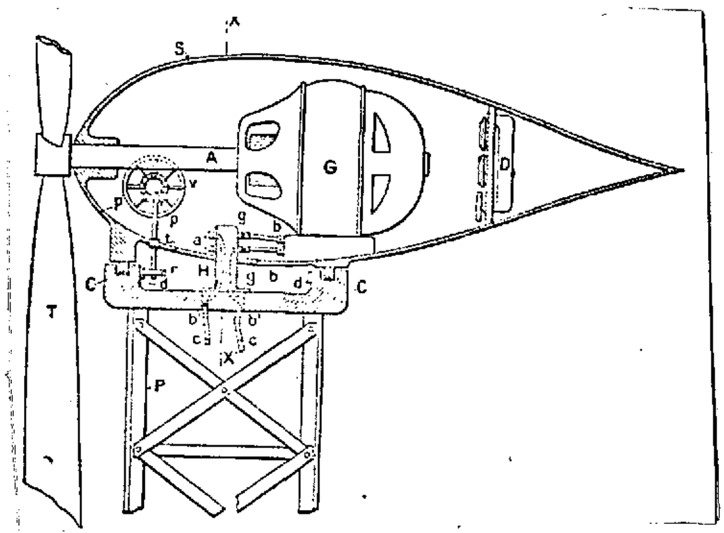

Fig. 53. Configuration of the upper part of a wind turbine-generator unit designed on the principles developed by Constantin.

Key: P. Pylon 27 m high.
T. Turbine with two blades 50 m in diameter.
S. Structure with low mechanical resistance enclosing the entire mechanism.
A. Coupling shaft.
G. Electrical generator.
D. Switchboard.
C. Track.
[Key continued on following page.]

p̄, p'. Orientation pinions.
v. Orientation wheel. (In practice, orientation will be automatic.)
d. Toothed orientation ring.
H. Central pipe for connections.
a, g, b, b' and c. Connecting members.
X and X'. Rotational shaft of assembly.

/92

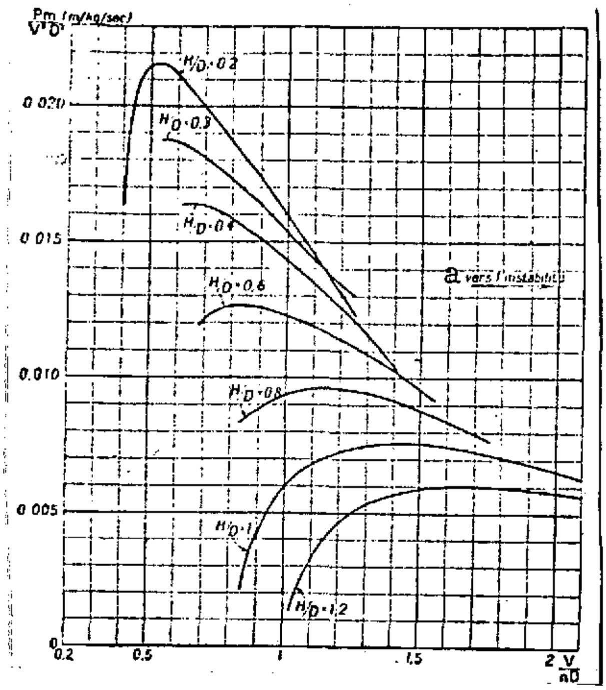

Fig. 54. Diagram of tests at the Eiffel Laboratory on the wind turbine model shown in Fig. 52. The power coefficients given in this diagram are expressed in kgm/sec. (To convert these coefficients into horsepower, divide by 75.)

Key: a. Toward instability.

Under the effect of the wind, this device merely orients the wind rose, which in turn activates a vertical shaft whose lower pinion drives a toothed ring secured to the base of the assembly, on the top of the pylon, which swivels the propeller. One advantage of this device is that during orientation of the propeller it does not produce the jerks and oscillations which occur with the use of a simple rudder or tail. /93

A lateral aileron serves to turn the plane of the propeller in the direction of the wind when the wind speed becomes excessive.

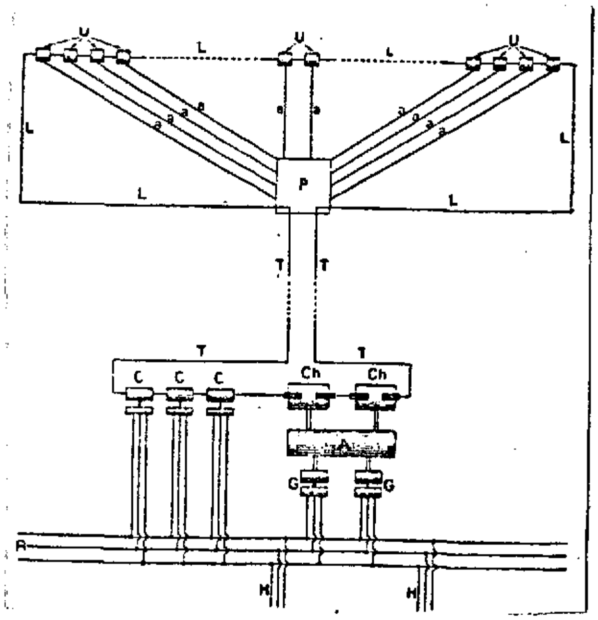

Fig. 55. General diagram of a wind power plant. A central station P is able to control an indefinite number of wind turbine units U. The junction cables a contain the pilot wires and the control lines serving to connect or short-circuit the units, to orient the turbines, etc. The general line L transmits all the energy produced in the form of direct current at variable voltage and current. This power, which is transmitted by lines T to a suitable point, is fairly erratic. It is converted into energy for home use, for example into a three-phase current with constant voltage and frequency, by means of converters C, electric boilers Ch, a steam accumulator A and electric turbine-generator units G. It is then collected by the collecting rods R and transmitted to the user circuits H.

Elementary Windmill Theory (developed by Darrieus, Engineer, Cie. Electro-Mécanique [Electromechanics Company], Paris and Le Bourget) /94

I. Introduction

The Göttingen School (Prandtl and his students, notably Dr. Betz) has already furnished a rational airscrew theory as part of the Lanchester-Prandtl airfoil theory. This theory is complete and definitive up to a given point; unfortunately, however, it was developed for propeller airscrews, and although adequate for this application, it is limited to the range which Prandtl has described as the linear or first-order range, that is, cases in which the perturbation speeds of the airscrew are relatively slight in com-

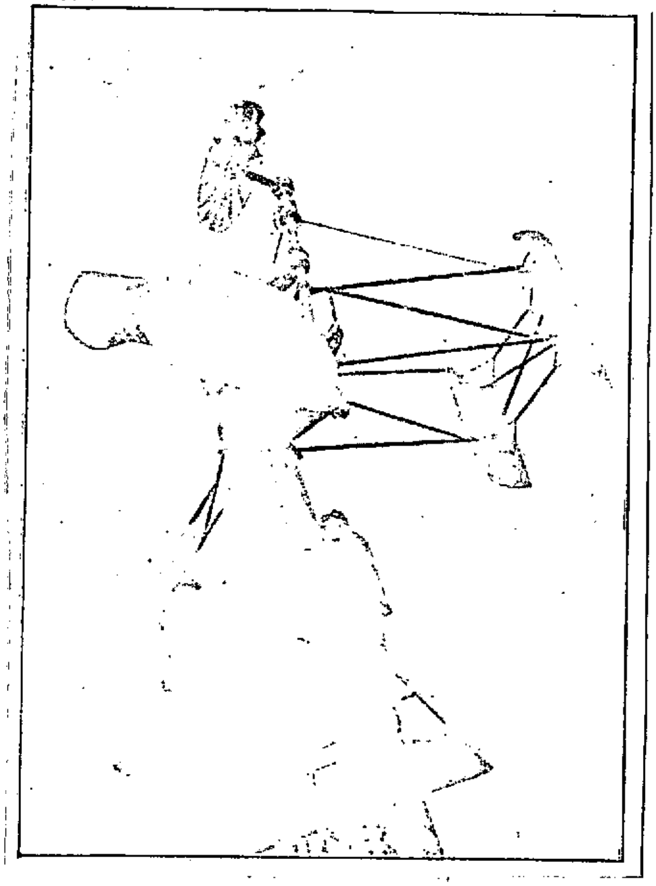

Fig. 56. Two-blade airscrew with the specialized orientation mechanism designed by Constantin, using a rudder with gutters and an auxiliary turbine known as a "wind rose." This wind motor has been in existence for nine years.

parison to the wind speed, so that the effect of the squares of these perturbation speeds can be set aside. The windmill, whose operating conditions are different, since the concept of efficiency has a completely different meaning here, with the result that the assumptions of the linear theory are not met, comprises a more general case. This is a finite problem for which a rigorous solution has yet to be found.

However, several important results which fortunately are practically significant can be obtained by the elementary method described below.[3]

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[3]We independently arrived at this elementary solution upon examining two articles by Dr. M. Munk and W. Hoff in the Zeitschrift für Flugtechnik und Motorluftschiffahrt, which gave many of the results described below, which had already been [continuation on following page]

II. Elementary Determination of Thrust, Power and Rate of Passage Through the Windmill

The power extracted from the wind by a windmill is the result of its borrowing a given amount of kinetic energy or momentum from the air masses passing through it. As a result, all the airstreams passing through the windmill are slowed from their initial speed V at a large distance upstream from the windmill to a residual speed V_0 downstream. (Fig. 57).

We will assume the tangential component of this speed to be negligible, either because the governing vanes have straightened the air currents by eliminating, by reverse torque, the kinetic moment transmitted to the fluid by the reaction of the motor torque, or, more simply, because the pitch of the vanes is small enough for the angular speed high enough that the effect of this torque can be overlooked.

It seems plausible to assume that the efficiency will be optimum if the residual speed v' is uniform throughout the entire cross section (although this can be demonstrated simply only if the cross section of the wake is given a priori). All the air /95
currents passing through the wheel thus yield the same quantity of energy $\frac{V^2 - v'^2}{2}$ per unit weight according to the Bernouilli theorem, since the pressure will be at the same level at a large distance upstream or downstream from the windmill.[4]

Thus the overall effect is as if the air, upon passing through the wheel, undergoes a sudden pressure drop of the same value, with the result that the total thrust exerted by the wind on the windmill becomes:

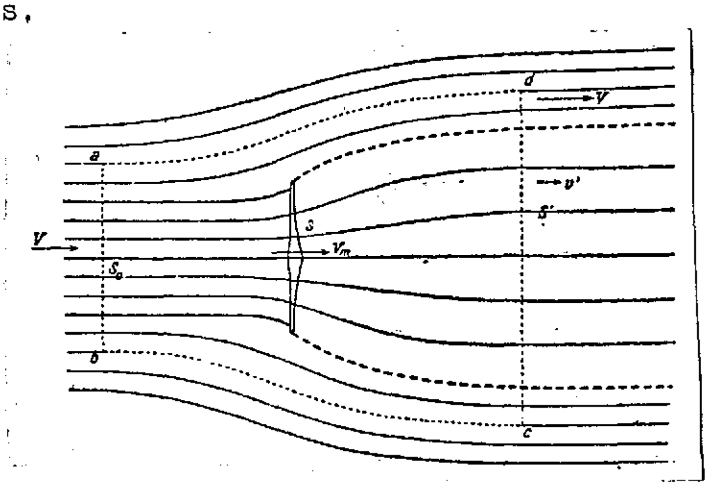
[con't from preceding page] obtained by these investigators.

It is all the more surprising that most French aircraft specialists, including the most recognized, appear completely unaware of these data, and are still relying on a totally empirical, rough, and hazy approach to the problem which hardly deserves to be called theory.

[4]The brief line of reasoning given here, which is that of the German investigators cited above, is inadequate and could lead to incorrect results. However, a rigorous demonstration, which, according to the Ampère theorem on the equivalence of lamina and currents, would require the introduction of equivalent imaginary sources in the vortex layer which bounds the wake, would be somewhat lengthy and will not be reproduced here.

$$P = \frac{\rho S(V^2 - v'^2)}{2} \qquad (1)$$

S being the cross section of the circle described by the tips of the blades.



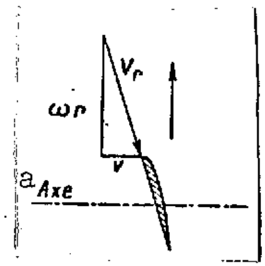


Fig. 57. Longitudinal section of wake, showing the indraft of slowed air and its separation from the ambient medium by a surface of discontinuity generated by the contour of the wheel.

Fig. 58. Composition of speeds in the vicinity of a blade cross section. Key: a. Axis.

Another expression for this thrust is furnished by considering the loss in momentum which the thrust produces in the air entrained by the wake. Let:

S' be the constant cross section of the wake at a fairly large distance downstream;

S_0 be the cross section of the corresponding current of fresh air of speed V at a large distance upstream; /96

and V_m the mean axial speed through the cross section S of the windmill.

Let us consider the closed surface composed of a tube of current abcd somewhat wider than the diameter of the windmill and limited by two fairly distant upstream and downstream cross sections ab and cd.

The pressures along this surface, which will be roughly the same as the uniform pressure P_0 at an extremely large distance from the windwill, will thus be in equilibrium, as will be the exchanges of momentum through the annular surfaces of cross sections ab and cd which surround the air current passing through the windmill.[5]

Thus the only contribution to the thrust on the windmill is a result of the excess momentum of the air mass entering cross section S_0 per unit of time at a speed V over that leaving cross section S' at a speed v'.

Denoting the air density by ρ, this contribution is thus:

$$P = \rho(S_0 V^2 - S'v'^2) \qquad (2)$$

Moreover, on the basis of the continuity equation:

$$S_0 V = Sv_m = S'v'$$

with the result that the thrust can be written as follows:

$$P = \rho S v_m (V - v') \qquad (3)$$

a form which, when equated with the first expression, yields:

$$v_m = \frac{V + v'}{2} \qquad (4)$$

The mean axial speed of the air passing through the windmill is thus the average of the initial and residual speeds of the wind, which generalizes a known result in linear propeller theory, where it in addition can be given a fairly simple specific interpretation (here the axial component v_m is uniform throughout the cross section).

The power, the product of the mass airflow and the energy /97 $\frac{V^2 - v'^2}{2}$ yielded per unit mass, thus has the value:

$$\boxed{W = \rho S v_m \frac{V^2 - v'^2}{2} = \frac{\rho S}{4}(V + v')(V^2 - v'^2)} \qquad (5)$$

Let us assume $\frac{v'}{V} = \alpha$; Eqs. (1) and (5) for the thrust and the power thus assume the form:

$$P = \frac{\rho S V^2}{2}(1 - \alpha^2) \qquad (1')$$

$$W = \frac{\rho S V^3}{4}(1 + \alpha)(1 - \alpha^2) \qquad (5')$$

See Fig. 60.

[5] See explanation 2 above.

III. Computation of Maximum Power

The maximum for this last expression, as a function of α, corresponds to $\alpha = 1/3$, that is, a residual speed equal to 1/3 the speed of the wind, or an average speed of the air passing through the windmill equal to 2/3 the wind speed.

At the same time, the ratios of the cross sections of the air current are $S_0:S:S' = 1:1.5:3$, and the maximum power is:

$$W_m = \frac{8}{27} \rho S V^3 = \rho S V^3{}_m = 0.2 \times 963 \rho S V^3 \qquad (6)$$

Thus the real power of a windmill of given diameter must be divided by this maximum theoretical power to determine the efficiency. All other methods, especially the fairly widespread method based on the total kinetic energy of an air mass passing through cross section S at a speed V per second, are arbitrary and should be discarded.[6]

Under ordinary atmospheric conditions at a low altitude, $\rho = 1.25$ kg/m^3, and as a result:

$$W_m = 0.370 \; SV^3 \qquad (7)$$

Assuming an efficiency of approximately 0.81, the maximum output of a windmill would therefore be 0.3 W/m^2 under a 1 m/sec wind, or 3 W/m^2 under a 10 m/sec wind. /98

IV. Digression on the Methods for Use of Wind Power

The above theory has made it possible to apply the principle results, especially thrust and power, on a wider basis than that of the weight alone; at any rate, as will be shown further, the detailed structure of the wake does contain all the essential characteristics of the mode of operation of the wind motor used. It is therefore applicable no matter what the specific mode of action or detailed design of this windmotor may be -- the number, speed or force of the blades in the case of a classical windmill with radial vanes.

At the same time, this theory demonstrates that the efficiency

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[6]The different method of determination used by Dr. M. Munk in the work cited above is based on other conditions (a windmill mounted on an airplane) under which the desired operating characteristics (low slipping and recoil) are fairly similar to those of a propeller.

of any system which does not tend to slow down the entire current of air passing through it, while at the same time keeping this air current at a uniform speed and structure, will be low -- even ridiculously low. This will be true no matter how ingenious or attractive the design or mode of operation of the blades may be.

From the outset, this dooms to failure most of the unfortunate attempts which are constantly being made to substitute for the classical windmill a model with its axis transverse to the wind (the "panemone," the Hottentot "Jumbo," the Little Giant, etc.), and especially the simple adaptations of various types of hydraulic turbines. In the latter case, the elimination of any uninterrupted partition between upstream and downstream, which will obviously be inevitable in air, makes it almost impossible for these units to function.

V. Analysis of the Operating Characteristics of the Classical Windmill

In the general theory given above, we have considered in the abstract the manner in which a windmill generates the sudden pressure drop in the air currents passing through it:

$$\Delta P = \rho \frac{V^2 - v'^2}{2}$$

this pressure drop being uniform over the entire surface area it encompasses.

Returning to the classical windmill with radial blades, this pressure obviously corresponds to the axial component of the thrust on the blade, whose tangential components additionally furnish the motor torque. /99

The expression for the total thrust on a blade element of length dr at a distance r from the shaft will be $f\ V_r\ \Gamma\ d\ r$, according to the Kutta-Joukowski theorem, with Γ being the circulation $\int V ds$ around the vane and V_r the relative speed, which consists of the tangential speed ωr and an axial speed v (with V_m being the average of this speed for the entire cross section S) (Fig. 58). If the friction is assumed negligible, a rational assumption on an initial approximation with the fish-shaped profiles, curved in the front and extremely slender in the rear, which are used in aircraft design, this thrust is in addition perpendicular to the direction of the relative speed V_r.[7] The

[7] More precisely, V_r represents the graphic mean of the relative speeds of the wind entering and leaving the wheel, according to an elementary theorem which Bauersfeld has demonstrated by adapting the Kutta-Joukowski theorem to turbines.

axial component of this thrust is therefore $\rho\omega r\Gamma dr$, and assuming that for the n blades of the windmill this axial component balances the uniform pressure on the corresponding ring $2\pi r dr$ of the cross section of the airstream, one obtains the condition:

$$\omega n\Gamma = 2\pi \frac{\Delta p}{\rho}$$

As a result, denoting $T = \frac{2\pi}{\omega}$ as the period of rotation and $\nu = \frac{n\omega}{2\pi} = \frac{n}{T}$ as the frequency of passage of the blades, the energy yielded per unit mass $\frac{\Delta p}{\rho}$ assumes the simple and significant form:[8]

$$\frac{n\Gamma}{T} = \Gamma\nu = \frac{\Delta p}{\rho} \quad (8)$$

VI. Computation of the Circulation in the Wake

This expression may again be obtained by another method which clearly shows the relationship between output and circulation, due to a classical assumption in turbine theory (Euler). Kinetic moment theory makes it possible to place the energy yielded to the fluid per unit mass in the form uc_u of the product of the speed $u = \omega r$ of the blade and the momentum c_u which its reaction transmits /100 to the fluid in the direction of the tangent. The expression for the circulation of the fluid around the axis, which is equal to the downstream circulation if there are no governing vanes (zero circulation upstream) is $2\pi r c_u$. This obviously represents the sum $n\Gamma$ of the circulations around each blade (Fig. 59), which once again yields Eq. (8) for the circulation, given above.

If, as we have assumed, the energy yielded $\frac{\Delta p}{\rho}$ is the same for all the airstreams passing through the windmill, the circulation is therefore constant in the wake along the entire length of the blades, and the circulation around the axis is also constant /101 throughout the wake. Here the motion of the fluid is still irrotational, except in the vicinity of shaft, due to the different zero value of the circulation,[9] and here the speed is derived from

[8]We may note the analogy -- which is not merely formal -- between this expression and that of energy quanta $h\nu$ of frequency ν in molecular physics.

[9]Which would require an infinite speed c_u on the shaft.

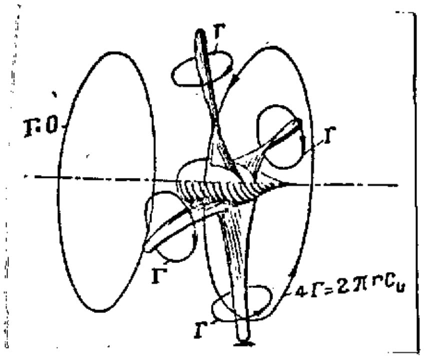

Fig. 59. Relationship between the circulation 4Γ transmitted to the fluid in the wake and the elementary circulation Γ around each blade on the wheel.

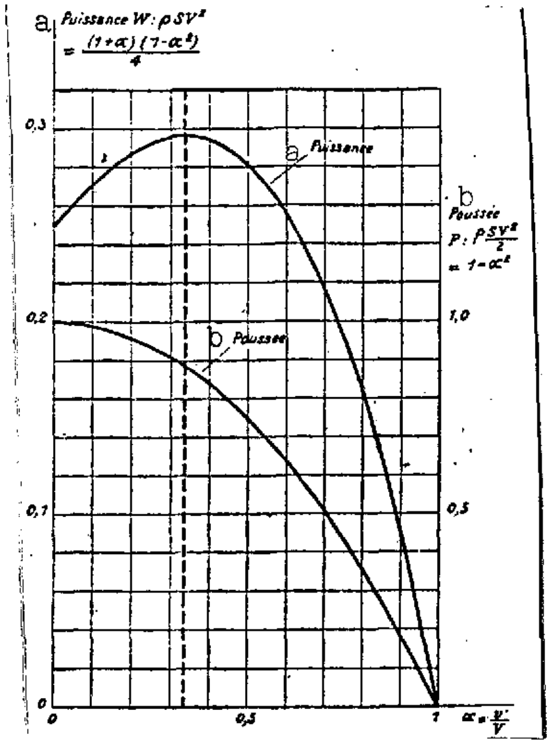

Fig. 60. Diagram of torque and and power as a function of the ratio α of the residual speed of the air to its initial speed.

Key: a. Power. b. Thrust.

a potential of multiple determination (polytropic).[10]

VIII. Bound Vortices and Free Vortices of the Field

According to the views of Lanchester-Prandtl, the constant circulation around the blades represents a bound vortex which, due to its properties of conservation of the vortex vector, is unable to stop at the blade tips and must continue in the fluid in the form of free vortices entrained by the wake, which are formed into helices by the relative movement of the wheel (Fig. 61). Those which separate from the blades in the vicinity of the blade root form the rotational nucleus for the irrorotational circulatory movement of the surrounding fluid, while those which describe the periphery at the blade tips are juxtaposed to form the surface of discontinuity shown in Fig. 7, which separates the wake from the ambient air.

At a point where the speeds of the fluid tangential to this surface are V_1 on the outside and V_2 on the inside (Fig. 63), the /102

[10] Reciprocally, the existence of a speed potential results in the uniformity of the constant of the Bernouilli theorem, that is, the energy yielded by the various airstreams.

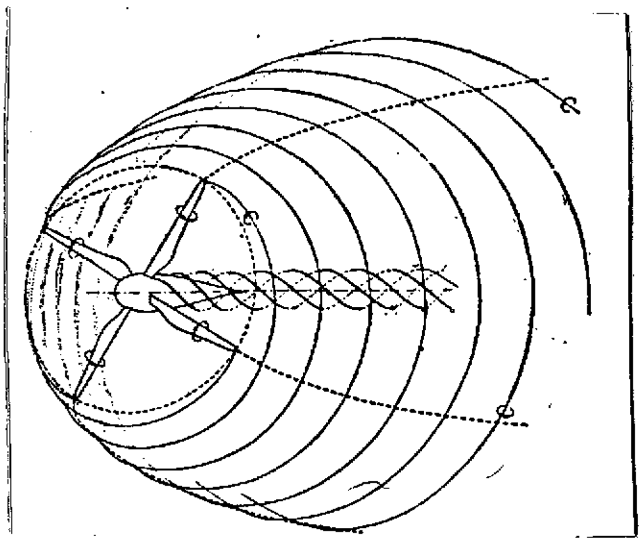

Fig. 61. Configuration of the free vortices which are extensions of the vortices bound to the blades through the fluid and form by their juxtaposition the two outside and inside boundary surfaces of the wake.

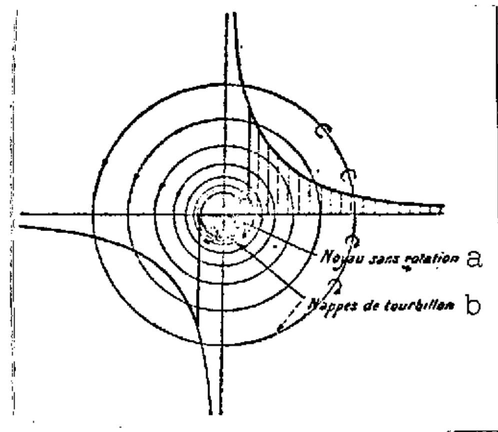

Fig. 62. Cross section of wake. The ordinates represent the tangential speed component in this plane.

Key: a. Non-rotating nucleus.
b. Layers of vortex.

value of the surface vortex, the total vortex per unit of length following a direction equal to the difference between these two vectors and normal to the latter in the tangent plane, is this same difference $V_1 - V_2$. Moreover, the flow rate of the free vortices around the windmill, which in a steady state is constant through a given point on the boundary layer of the wake, is $\Gamma\nu$ per unit of time. In other words, the flow rate is precisely the energy $\frac{V_1^2 - V_2^2}{2}$ per unit of mass of the airstreams in the wake in comparison to the ambient air.

The speed of entrainment of the vortices is therefore:

$$\frac{V_1^2 - V_2^2}{2} : (V_1 - V_2) \text{ or } \frac{V_1 + V_2}{2}$$

that is, the average of the speeds on either side of the discontinuity,[11] in conformity with a general proposition (Helmholtz),

[11] Along the lines of the movement of the ring of rollers in a pivoting bridge or windmill.

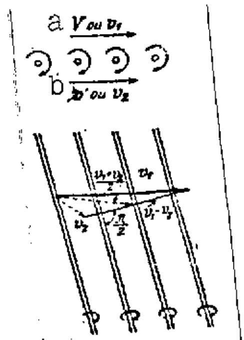

Fig. 63. Relationships between the speeds ν_1 and ν_2 on either side of the plane of discontinuity and the lamellar vortex $\nu_1 - \nu_2$ located in this plane.

Key: a. V or ν_1.
b. ν' or ν_2.

expressed as an equation of continuity for the vortex tubes of variable intensity which sweep the surface.

VIII. The Use of Governing Vanes

In the case of a propeller, or in the analogous case of a windmill turning in stationary air, the rotational movement transmitted to the air in thewake requires additional momentum, and obviously constitutes a loss which a good design will seek to reduce as much as possible. Another aspect of this loss is the negative pressure which generates centrifugal force in the axial region of the wake, and which, decreasing the useful thrust for the propeller or increasing the mechanical resistance of the windmill, lowers the efficiency in both cases.

This is not the case with an ordinary windmill secured on the ground. Here the additional momentum corresponding to the tangential speed c_u is acquired merely by additional borrowing from the potential energy of the wind. The only resultant losses are the corresponding negative pressure in the wake and a given amount of additional thrust which is usually slight at any rate and does not produce any work since the windmill is in a fixed position.[12]

Moreover, this result could be predicted due to the irrorotational nature of the movement on either side of the wheel, which requires an equal Bernouilli's constant and equal work yielded for all the airstreams. The only disadvantage to this gyrational movement is that, due to the impossibility of attaining infinite speeds c_u within the axis of the wake, the use of the airstreams closest to the shaft is necessarily zero, even when the wheel hub is streamlined (Fig. 64). This could in no way prevent the formation of a nucleus of limited angular speed along the axis, and consequently circulation of the air becoming cancelled at the center. However, the loss involved, reduced to a central cross

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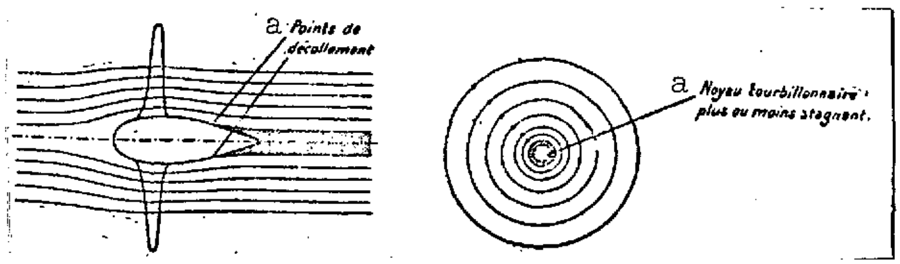
[12]Strictly speaking, the only remaining loss is an insignificant one which is equal for all the airstreams at a minimum value of $\frac{c_u^2}{2}$ at the tips of the blades, while the corresponding term for the airstreams close to the shaft could become quite high in slow windmills with a large number of blades (high $n\Gamma$ and c_u), if it were not compensated for by the corresponding negative pressure.

section which can be minimal, is generally not very significant.

In addition, it is possible to cancel the rotation of the air around the shaft in the wake by compensating for the tangential speed c_u transmitted to the air upon passing through the wheel with an equal and opposite c_u produced by governing vanes positioned up- and downstream.[13]



Figs. 64-65. The necessary production of a rotational nucleus along the axis of the wake when the circulation around the wake is not zero.

Key: a. Points of separation.
b. More or less stagnant nucleus of vortex.

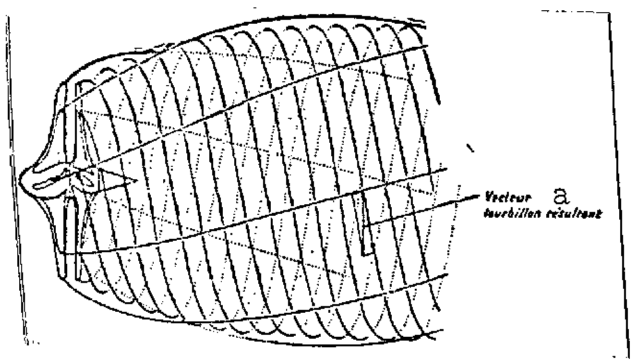


Fig. 66. Annulation of the circulation in the wake and elimination of the internal nucleus of free vortices by the addition of governing vanes.

Key: a. Resultant vortex vector.

The outside tips of these vanes will also be the point of origin of free vortices, which, like those generated by the wheel, wheel, will wind helicoidally along a surface of discontinuity. The circulation around the axis will remain only in the annular interval between the two surfaces of discontinuity, which in addition may coincide; correlatively, the vortices bound to the blades of the wheel may be followed through the hub by similar

[13]This arrangement has already been tested successfully in the case of a propeller (contrapropeller), for which it is better suited.

vortices bound to the governing vanes (Fig. 66), rather than generating free vortices entrained by the axis of the wake, as previously. At the same time, with a streamlined hub it becomes impossible to use the entire cross section of the airstream up to an area close to the center. Together, the two systems of helicoidal vortices which now delimit the wake constitute a sort of fabric, in which the elementary vortices form to cancel their axial components, allowing only a tangential component to remain (Fig. 66). As a result, the real surface of discontinuity, whose detailed structure has little final significance, is finally equivalent from the standpoint of its external effects to a regular chain of annular vortices, each with the intensity Γ, continuously originating at the periphery of the windmill at a rate of /105

$\nu = \frac{n}{T}$ (frequency) per second.

In the strictest sense, the initial computations given above refer to these ideal conditions: zero internal circulation and a very high number of blades or a high rotation speed.

Given these assumptions, the vortices of the wake may be said to originate in the following manner. If one considers the windmill as a circular surface of discontinuity for pressure, or, amounting to the same thing, a system of two extremely proximate equipotential surfaces between which there is a uniform, extremely intense force field,[14] the energy exchange occurs through the resultant extremely brief impetus which the airstreams receive upon passing through the windmill.

Thus the forces applied to the entire airstream are uniformly derived from one potential. Consequently, in accordance with the Cauchy-Helmholtz theorem, the initial irrorotational nature of the movement, except within the force field, where a fluid mass such as abcd (Fig. 67) is subjected to the lateral effects of the resistance of the windmill as this mass passes through this single point, will now acquire a given kinetic moment in the direction of the arrow, producing an annular vortex.

In the final analysis, the slight theoretical superiority does not justify the addition of governing vanes, even limited to the central region[15] (Fig. 68), at least in the case of windmills, nor does it even compensate for the additional frictional losses introduced. Actually, the Bollée turbines, for example, cannot be expected to have a higher efficiency than simpler ordinary windmills. /106

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[14] Similar to that of a condenser, but without marginal leakage.

[15] The only area in which it is worthwhile a priori to combat the rotational movement.

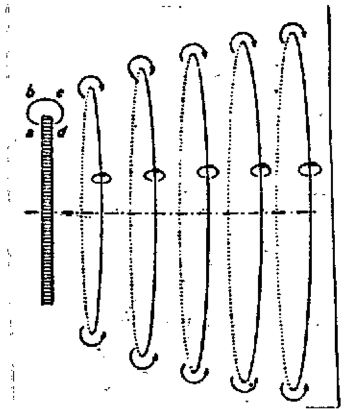

Fig. 67. Chain of annular vortices equivalent to the resultant, without axial component, the two systems of helicoidal vortices shown in Fig. 66.

IX, Choice of Number of Blades

As we have seen, the basic general operating characteristics, all of which may be observed in the structure of the wake, depend only on the retardation of the airstream as it passes through the windmill, or the intensity $V - v'$ per unit of length of the surface vortex which bounds this airstream. If Γ is the intensity an elementary vortex tube corresponding to the wake of one blade and d the distance between two consecutive airstreams, the intensity of this surface vortex will be Γ/d (Fig. 69). Now,

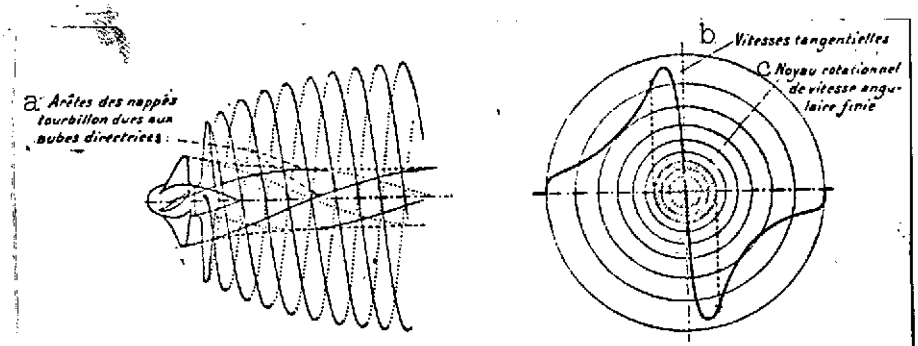

Fig. 68. Annulation of the circulation, in the vicinity of the shaft alone, by the use of short governing vanes.

Key: a. Peaks of the vortex layer generated by the governing vanes.
b. Tangential speeds.
c. Rotating nucleus of finite angular speed.

$d = \frac{p}{n}$, with p representing the pitch of each helix equal to the product $\frac{V + v'}{2}$ T of the axial speed $\frac{V + v'}{2}$ of the chain of vortices and the period of rotation T.

Thus the product $\frac{n}{T}$ of the number of blades and the rotation speed is the only factor which comes into play. As a result, the /107

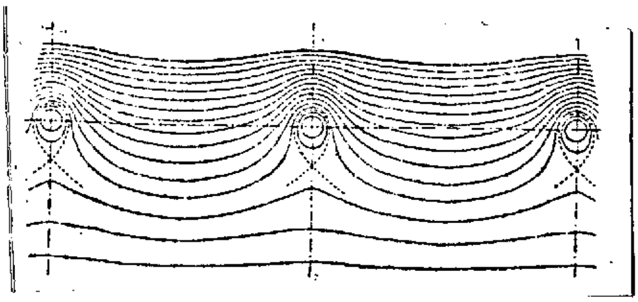

Fig. 69.

same output will be obtained, either with a large number of blades with a wide pitch and a low speed (American windmill, Fig. 71), or with a small number of blades of small pitch and a higher speed p (Dutch and modern windmills, Fig. 72). The advantage of a high specific speed is not only to decrease the torque and installation costs, but also to reduce the rotation of the wake. Theoretically, a single, extremely narrow blade of relatively fine pitch, rotating fairly quickly -- and consequently a two-blade airscrew such as an aircraft propeller -- can be expected to produce the same useful effect as a wheel with a large number of blades and a large total area. However, in practice it is preferable to use no less than three or four blades, as in classical windmills, to obtain sufficiently regular torque even with a non-uniform wind. /108

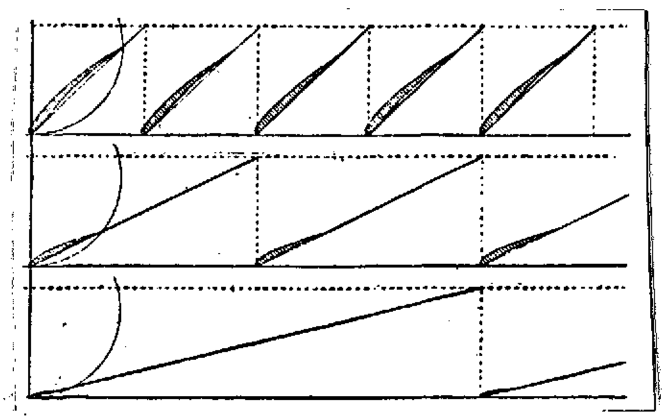

Fig. 70. Comparison of three equivalent vane configurations. Tangential speeds and specific speeds (the total airfoil surface is in inverse proportion to the square of the speed).

Furthermore, the indefinite increase in specific speed is limited by the proportional increase in frictional losses and by the increasingly marked relative inadequacy of the starting torque, which decreases approximately in inverse proportion to the square of the speed.

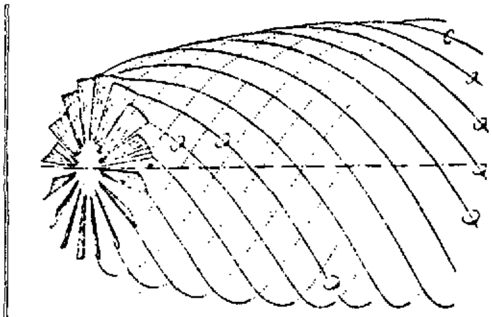

FIG. 71.

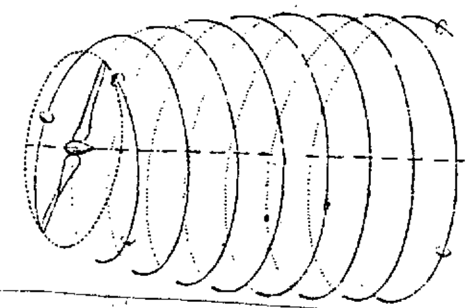

FIG. 72.

Figs. 71 and 72. Comparison of two windmills. American type with airfoil surface [sic], Fig. 71, and Dutch or modern type with small airfoil surface, Fig. 72. The output is the same (the density of the vortex streams on the contour of the wake is the same), but the angular speed is different.

X, Determination of Shape of Blades

When the angular speed, the number of blades and the retardation of the wind in the wake have been fixed, the distribution of vortices will result, and the entire velocity field of the air, especially upon passing through the wheel, will be determined. This is because, according to classical theory, the velocity field superimposed on the initial wind speed by the action of the propeller may be derived, at each point, from the combination of free and bound vortices in the field, just as the magnetic field at the same point may be derived from imaginary electrical currents of the same distribution and intensity as these vortices (Laplace and Biot-Savart laws).

Consequently, in practice the mode of action of each blade element depends only on its transverse profile and the speed vector of the entire system in its vicinity, with the exception of this blade element (but including the other blades, whose effects are cancelled due to symmetry in a wheel with radial blades).

This is the fundamental hypothesis of airfoil theory. Well-founded in the limited case of infinitely slender blades, it remains plausible in most practical cases and has received abundant confirmation, both in the remarkable success of subsequent theoretical analysis and in the special tests to confirm it which have been performed, especially by the National Physical Laboratory in England.

This approach to the problem, the only rational approach today, /109
combines, in an appropriate determination of the speed of the air relative to the airfoil, all the complex mutual effects which many aerodynamics specialists still designate by the vague and frequently outdated term "interactions."

With regard to this speed, the vane element behaves as a blade of infinite length, with the result that there is no reason to introduce the consideration of any more or less well-defined imaginary extension of the vane by drawing on wind tunnel tests of individual vanes, whose behavior, moreover, is quite dissimilar.

XI. Choice of Blade Profile

On the other hand, thesessame tests eliminate the mechanical resistance and the dynamic resistance, also termed the induced resistance, which according to Lanchester and Prandtl result from the limited span of the airfoil. As a result they make it possible to obtain the true intrinsic or airfoil resistance for this limited profile, which is the only resistance determined by these tests which should be used in other applications.

The results are generally plotted as "polar" curves with the component P of the thrust perpendicular to the relative speed given as the ordinate and the component D parallel to this speed as the abscissa, the latter being the mechanical resistance or drag.[16] The latter, which is theoretically zero in a frictionless fluid and with a streamlined airfoil with a sharp trailing edge, within the limiting angles of incidence which do not give rise to separation, becomes smaller as the airfoil, assumed to be sufficiently smooth, becomes thinner and sharper to the rear. In the most efficient profiles, similar to those of a bird's wing or the body of a fish, the trailing edge is not only acute, but is not turned back for a suitably hollowed contour on its two posterior surfaces.[17] The typical shape is furnished by the Joukowski profiles (Fig. 73), /110 theoretically derived by this investigator from purely analytic considerations. These would be the most advantageous due to the excellent P/D or "fineness" ratio, if they were not so difficult

[16]It is to advantage to replace these components with the dimensionless lift and drag coefficients C_L and C_D by dividing them, first, by the airfoil surface, and second, by the kinetic pressure or stagnation-point pressure $1/2\ \rho\ V^2$ (maximum overpressure at the front of the airfoil, point A in Fig. 73).

[17]Contrary to persistent practice, to be suited for varied angles of attack, the airfoil should have no angular point other than the trailing edge. The rounded contour of the leading edge should not enforce a specific position for the point of origin A of the airflow lines.

Moreover, tests have shown that the lift coefficients which are compatible with high efficiency, whichaare higher as the overall curvature of the airfoil increases, in addition fall into a narrower range as the forward radius of curvature decreases.

to construct due to the extreme thinness of the trailing edge. Fig. 74 shows a typical polar for a good practical profile; the minimum D/P ratio (inverse fineness ratio) given by the tangent issuingfrom the point of origin generally corresponds to a lift coefficient close to 0.80 and drag which is sometimes less than 0.01.[18]

Having chosen the most favorable lift coefficient, which simultaneously leaves an adequate margin of 50:100 of additional thrust prior to separation,[19] we are now ready to determine the width for the blades as a function of the radius. Equalizing the expression of thrust $\rho\ V_r\ \Gamma$ dr given by the Kutta-Joukowski theorem with that resulting from the determination of C_L, $P = C_L\ l dr\ \frac{1}{2}\ \rho\ \frac{V^2}{r}$, we obtain the equation: /111

$$\Gamma = C_L\ \frac{l \ell V r}{2} \qquad (9)$$

The width ℓ of theblade should therefore decrease from the root to the tip in inverse proportion to the speed Vr, if, as we have assumedthe circulation is constant along the vanes. At the same time, the Reynolds number $\frac{Vr\ell}{\nu}$ (where ν is the kinematic viscosity, the quotient of the absolute viscosity divided by the density), a pure number on which the small differences between results for geometrically similar profiles exclusively depend, is constant over the entire length of the vane. The same polar can thus be used from one end to the other if the shape of the cross section remains appreciably constant, and the same will be true of the ratio D/P corresponding to a given lift coefficient C_L.

To determine the relative speed V at each point on the vane, it would be necessary to know the axial speed V_m distribution along the radius. Basic theory furnishes only an average value for V_m due to the lack of a rigorous solution for this problem, which so far has not been solved, even in regard to the ideal conditions weare considering here. In this regard the following discussion will merely give a few qualitative indications; we

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[18] The fineness ratio P/D may be as high as 120 with the thinnest Joukowski profiles, with Reynolds numbers on the order of 500,000.

[19] Separation, marked by an increase in drag, corresponds to a lift coefficient C_L of 1.20 to 1.40.

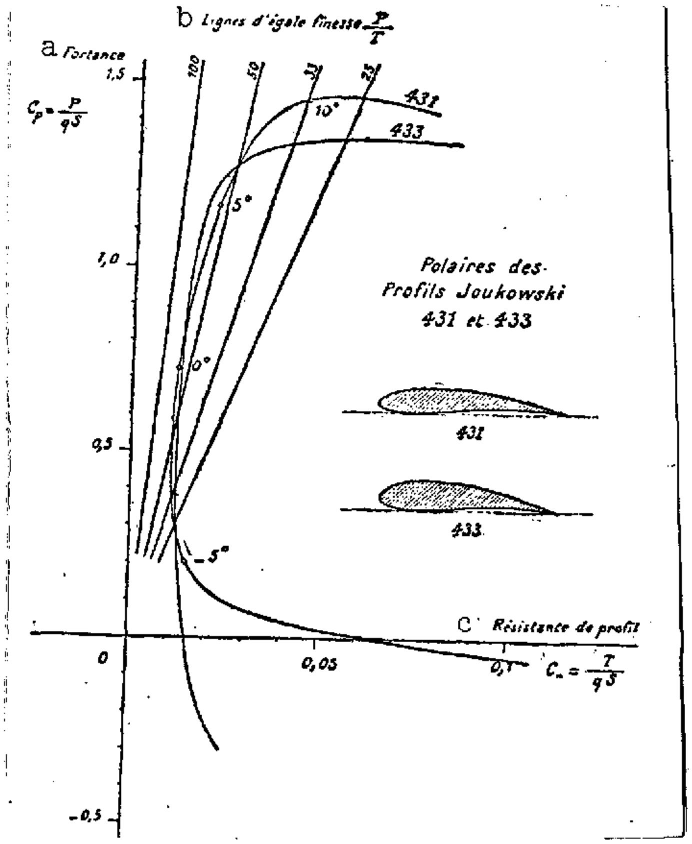

Fig. 73. Polars of Joukowski profiles 431 and 433.

Key: a. Lift. b. Lines of equal fineness P/D.
c. Strength of profile.

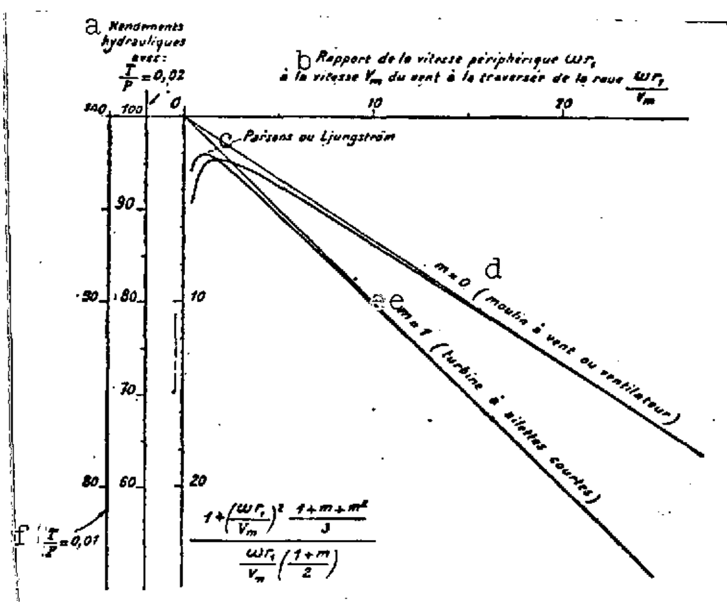

Fig. 74.

Key:

a. Hydraulic efficiencies with: D/P = 0.02.
b. Ratio of the peripheral speed ωr_1 to the speed V_m of the wind passing through the wheel $\frac{\omega r_1}{V_m}$.
c. Parsons or Ljungstrom.
d. m = 0 (windmill or fan).
e. m = 1 (short-bladed turbine).
f. D/P = 0.01.

will temporarily assume in the following that the axial speed V_m is uniform over the entire cross section of the windmill and equal to its average value (for example, 2/3 V at maximum power).[20]

XII. Computation of Frictional Losses

Due to the drag D dr caused by friction, each element of length dr of the blades generates a loss in power $V_r D dr$.

In addition, the corresponding forward thrust is Pdr = $\rho V r \Gamma dr$, with the result that by introducing the ratio D/P, the elemental loss may be written:

$$\frac{D}{P} \rho V_r^2 \Gamma \, dr, \quad \text{or} \quad \frac{D}{P} \cdot \rho \Gamma (V_m^2 + \omega^2 r^2) \, dr$$

since V_r is composed of the wind speed V_m and the speed of the vane ωr.

The loss, integrated from the internal radius r_0 to the external radius r_1 of the vane, is therefore:

$$\frac{D}{P} \cdot \rho \Gamma \int_{r_0}^{r_1} (V_m^2 + \omega^2 r^2) \, dr$$
$$= \frac{D}{P} \rho \Gamma V_m^2 r_1 (1 - m) \left[1 + \left(\frac{\omega r_1}{V_m}\right)^2 \left(\frac{1 + m + m^2}{3}\right) \right]$$

assuming $m = \frac{r_0}{r}$.

The tangential or useful component of the elemental thrust $\rho V_r \Gamma dr$, moreover, is $\rho V_m \Gamma dr$, which produces an elemental power $\rho V_m \Gamma \cdot \omega r \, dr$, with the result that the total power is: /113

$$\rho \Gamma V_m \int_{r_0}^{r_1} \omega r \, dr = \rho \Gamma V_m \frac{\omega r_1}{V_m} \frac{1 + m}{2}$$

Thus the relative loss or complement of the efficiency η at unity is:

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[20] Most investigators who have developed windmill calculations assume this speed to be equal to the wind speed, which is grossly incorrect.

$$1-\eta=\frac{D}{P}\left[\frac{1+\left(\frac{\omega r_1}{V_m}\right)^2\frac{1+m+m^2}{3}}{\frac{\omega r_1}{V_m}\,\frac{1+m}{2}}\right] \tag{10}$$

If m and $\frac{D}{P}$ are given, the efficiency will be maximum with a ratio $\frac{\omega r_1}{V_m}$ of the peripheral speed to the axial speed equal to:

$$\left[\frac{\omega r_1}{V_m}\right]_{\eta max}=\sqrt{\frac{3}{1+m+m^2}}$$

If the ratio of the radii $m = \frac{r_0}{r}$ is extremely small, this value will reach $\sqrt{3}$ (assuming $V_r = 2\ V_m$), and the corresponding minimum for the bracketed factor will be $\frac{4}{\sqrt{3}} = 2.31$, with the result that with a $\frac{D}{P}$ ratio equal to 0.02, the hydraulic efficiency of the windmill will already be greater than 95% (Fig. 74).

If the ratio $\frac{r_0}{r}$ is close to unity, on the other hand (axial compressors or turbines), the optimum ratio $\frac{\omega r_1}{V_m}$ is unity, a result which is very close to that obtained by the Parsons or Ljungström blade systems, and which explains their excellent efficiency.

From the standpoint of efficiency alone, it would be best to use moderate speeds and blades at a fairly elongate pitch, as in the American windmills. The starting torque would be fairly high at the same time, but the area exposed to the air and the weight would be excessive.

On the other hand, it would be to advantage to make use of the fact that the D/P ratios are extremely low with well-streamlined smooth profiles (sometimes less than 0.01) to obtain much higher specific speeds, as soon as it becomes possible to compensate for /114
a 20% loss, for example, merely by increasing the diameter of the windmill by 12%.

The attached diagram (Fig. 74) thus shows that with

$\frac{\omega r_1}{V_m} = 10$ and $\frac{\omega r_1}{V_m} = 20$, at m = 0 the bracketed expression in Eq. (10) does not exceed 5.72 and 12.23, respectively, that is, approximately three and six times the minimum. As a result, even with a $\frac{D}{P}$ ratio as high as 0.02, the hydraulic efficiencies would still be 88% and 75%, respectively. Unfortunately, the starting torque would generally be inadequate in the latter case, except in certain applications.[21]

XIII. Approximate Determination of Twist of Blades

In the linear airscrew theory developed by Prandtl, the wake is cylindrical from the point of origin, and throughout the cross section the axial speed upon entrance is equal to its average v_m computed above.

In the case with which we are concerned, in which the perturbation caused by the airscrew is no longer infinitely small, the axial speed through the wheel ceases to have a uniform distribution, while retaining the same average value.

On either side of the surface of discontinuity which delimits the wake there is a constant difference $V_1^2 - V_2^2$ between the squares of the speeds of the fluid. This negates the assumption that two airflow lines which are contiguous at first and are destined to pass on either side of the surface of discontinuity could separate at the actual edge of the surface.

In the theoretical case with which we are concerned, that of an infinitely thin surface of discontinuity generated by an infinity of infinitely slender vortices arriving from an infinite number of blades, one finds on the other hand that the forward edge of the surface of discontinuity constitutes a characteristic line defined by the airflow lines, on which the speed becomes infinitely high (Fig. 75).

Correlatively, the vortex of surface $V_1 - V_2$[22] here is infinite, /115 and as a result, the rate of transverse motion $\frac{V_1 + V_2}{2}$ of the

[21] As for the values of $\frac{\omega r}{v_m}1$ cancelling the efficiency (loose wheel), they would be approximately 75 and 150, respectively, for $\frac{D}{P} =$ 0.02 and 0.01 (at high speeds ωr_1 the bracketed expression tends toward $\frac{2\omega r}{3v_m}1\frac{1}{2}$).

[22] The assumption of infinitely slender, but infinitely small and numerous vortices occupying a continuous surface does not necessarily mean that there will be infinite energy and infinite loss in the wake, as it does in the case of linear vortices (a single wing or vane, for example, with uniform lift distribution).

vortices is no longer zero.

The elemental vortices are thus especially close together in the forward part of the wake, and they assume their final speed $\frac{V + v'}{2}$ and spacing only gradually.

Thus an internal point A beyond the wheel serves as the point of origin for the airflow lines which will follow a path respectively on the outside or the inside of the wake. The speed is cancelled on the inside, and reaches a minimum,

$$V_{1\ min}^2 = V_1^2 - V_2^2 = V^2 - v'^2$$

on the other side of the surface.

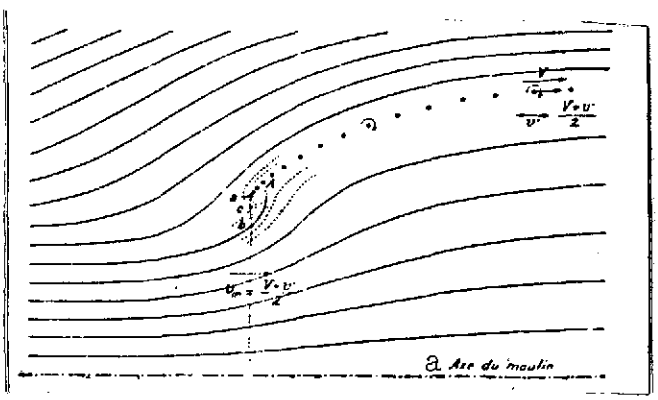


Fig. 75. Longitudinal section showing the arrangement of airflow lines and the partial reflux of the air in the vicinity of the wheel.

Key: a. Shaft of windmill.

A reflux of air from the rear to the front thus occurs on the periphery of the windmill, and an entire annular area ab through which the same air currents pass two different times in opposite directions does not contribute to the power of the assembly.

At first glance, this partial partial fan-wise operation is a fairly strange phenomenon, and it is paradoxical that this negative local work could be the essential condition for optimum use of the given span of the windmill. Nevertheless this is in fact the case, and one can easily see that if the /116
outside region of the vanes, which tends not to "lift" (due to the fact that the ambient air "short-circuits" it, so to speak), still does not maintain any thrust on the air attempting to escape it by turning around it, the final diameter of the wake, and, as a result, the total power will necessarily be lowered.

To obtain these conditions, the pitch of the airscrew should be zero in the vicinity of point C and become negative beyond this point, at least in the extreme theoretical case being considered here, that of an infinite number of vanes. The only one of these observations which should be taken into account in practice is that the pitch of the vanes, far from being roughly constant as most designers make it, should decrease rapidly and tend toward zero close to the tip.

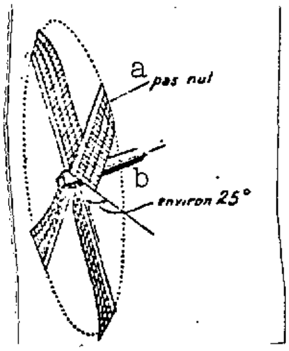


Fig. 76. Detail of the design of the classical Dutch windmill: the pitch decreases rapidly and becomes zero at the tip of the vane.

Key: a. Zero pitch.
b. App. 25°.

Now, it is remarkable that the old windmills found in our countryside since time immemorial, as the paintings of the Dutch masters show, satisfy precisely this condition (Fig. 76), which to our knowledge had not yet been given any theoretical interpretation, and which moreover has fallen into disuse in modern design. Nevertheless sharp intuition and a keen sense of observation had undoubtedly introduced it into the tradition of the old designers at an early date. Moreover, the lack of observance of this condition must undoubtedly be considered partially responsible for the lack of power which is clearly demonstrated by modern tests performed with satisfactory profiles which should achieve better efficiency.

XIV. Effect of a Finite Number of Blades

The limiting case of an infinite number of blades, which we have just examined, places no restriction on the theoretical condition which subordinates the attempt to obtain maximum power with a given span to that of obtaining constant circulation over the entire length of the blades.

This is not the case with a finite number of blades, since the free vortices of finite intensity suddenly formed at the tips of the blades in this way will be infinitely slender, and would produce infinite kinetic energy, although this would occur in a volume which would decrease as their frequency or proximity in- /117
creased.

Correlatively, the reflux rate developed by these vortices in the immediate vicinity of the blade tip (Fig. 77) would require a highly negative pitch for the blades, and would give rise to an extremely high "induced" resistance under this element.

To prevent this, as in all similar cases in airfoil theory, the circulation must gradually be decreased toward the tip of the vane, distributing the free vortices released in this way along the trailing edge, over a length proportional to the spacing between consecutive free vortices.

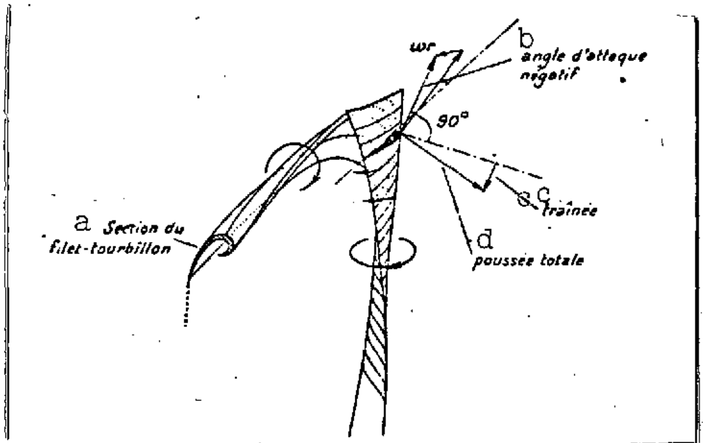


Fig. 77. Posterior view of a vane tip showing the distribution of vortex streams in a surface of discontinuity of the speed, gradually turning in upon itself.

Key: a. Cross section of vortex stream.
b. Negative angle of attack.
c. Drag.
d. Total thrust.

The problem of optimum lift distribution has been solved by Dr. Betz, in a form, however, limited by the assumptions of linear theory, as applied to the propeller, for example.

In the general case with which we are concerned, this problem unfortunately remains insoluble and must be supplanted by a random outline whose practical repercussions on the operation of the whole will be of minimal importance.

Fig. 78 shows how these vortex surfaces, whose intensity, which is zero toward the shaft, rapidly becomes extremely high at the tip, immediately after originating in ab in the wake of the trailing edge begin to wind in increasingly tight spirals which are entrained by the airstream. At a large dis- /118
tance downstream, these spirals more or less uniformly fill nuclei which are appreciably circular in cross section, where the viscosity tends to equalize the rotation speeds. These nuclei, which at first form a regular chain, gradually scatter to one side or the other, and, smoothing the contours of the wake, ultimately efface it completely as the airstream becomes homogeneous once again.

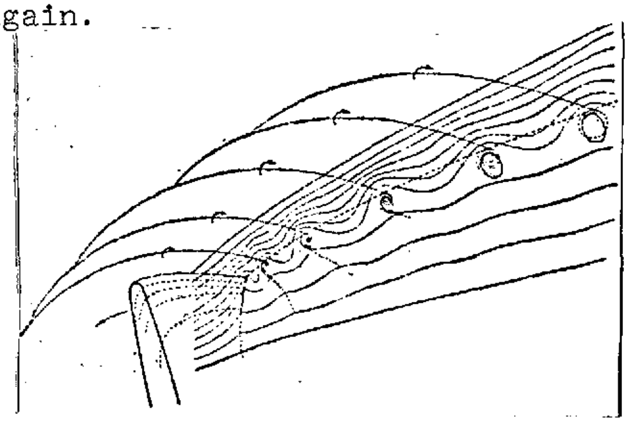


Fig. 78. Detailed structure of the contour of the wake, showing the progressive convolutions of the vortices of which it consists.

The Darrieus Wind Motors

(Developed by G. Lacroix, Engineer, Electro-Mécanique Co.)

Description of the Installation

The types of wind motors designed by Darrieus have been constructed by the Electro-Mécanique Co. on the land adjacent to its plants in Bourget. They have been analyzed with respect

to theoretical data. These are high specific speed windmills; thus they rotate rapidly and have narrow vanes, especially at the tips, a necessary condition for obtaining high speeds. In fact, their light and slender appearance never fails to surprise anyone used to Dutch or American windmills, which have much larger airfoil surfaces. This low blade surface area permits these windmills to remain stopped (or in operation) during the most violent storm winds without the necessity for deflecting the wheel. Moreover, given their high rotation speed, in normal operation the blades are already subjected to a relative wind of the same order of magnitude as the most violent winds they might encounter in this region when stopped. To diminish their fatigue, the blades have been inclined to the rear so as to bring into play the centrifugal /119
force, which, like the thrust of the wind, is proportional to the square of the rotation speed or the wind speed. Under these conditions, the combined thrust of the wind and centrifugal force remains constantly directed in the general direction of the blade. Consequently it is unnecessary for the blade to withstand any bending stresses during normal operation (Fig. 79).

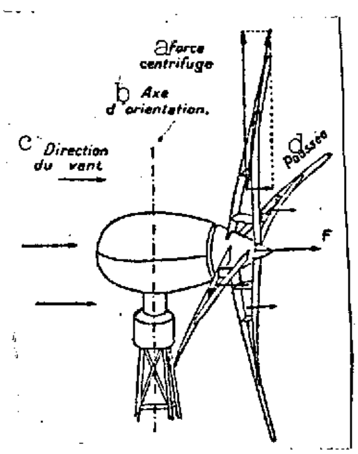


Fig. 79. The Darrieus electric wind generator. The inclination of the blades to the rear is such that the combination of centrifugal force and thrust on each blade is constantly directed in the general direction of the blade, which eliminates bending stresses. The combined thrust F on the four inclined blades keeps the windmills facing into the wind.

Key: a. Centrifugal force.
b. Pivoting shaft.
c. Direction of wind.
d. Thrust.

Another interesting characteristic is the biplanar design of the blades. Each blade consists of two juxtaposed vanes of unequal length, assembled at a fairly acute angle and connected by spacers and, in some cases, diagonals. It is extremely difficult to construct long, single-plane blades with sufficient rigidity, especially if they are not tilted to the rear. The only two possible solutions are the use of an inside frame or outside bracings. The use of an inside frame results in extreme thickness of the blade at the root, at the expense of aerodynamic performance. Outside bracings or guy-wires, which are too often used, introduce tremendous parasitic resistances which lower the efficiency of the wheel. A biplanar or multiplanar blade design makes it possible to obtain adequate tail-in at the root, while retaining a relatively thin blade profile to ensure high efficiency. The spacers or diagonals are also contoured to introduce as low a resistance as possible; in any case, this will be much less than that of the steel wires generally used as guy-lines.

The profile used for the blades is a Joukowski profile with an extremely high aerodynamic efficiency. The aerodynamic characteristics of this blade design are well-known due to the measurements performed in the Göttingen laboratory.

In all cases, the purpose was to generate electrical power, an operation suited to low starting torque. The windmill uses multiplying gearing to drive an ordinary generator, and the /120
assembly is placed in an impervious enclosure at the top of the pylon, eliminating the necessity for any mechanical transmission to the ground (Fig. 79). The generator is equipped with an automatic excitation regulator which at the same time ensures parallel operation with the storage battery.

These windmills do not have any orientation system. The wheel is simply mounted downwind from the pylon and the enclosure (an arrangement facilitated by the rearward tilt of the blades), with the result that the windmill orients automatically under the thrust of the wind in the manner of a rudder. Since the windmill cannot be halted by deflecting the wheel, this is obtained by means of a mechanical band brake or brake with shoe controlled from the ground and also able to operate automatically when the speed of the windmill reaches a given level (overspeed).

The use of a high specific speed provides the windmill with one extremely attractive characteristic: automatic power limitation when the wind speed increases. If a given method is used to prevent the speed of the windmill from increasing as rapidly as the wind speed, the angle of attack increases, and when it has reached a level corresponding to critical incidence, the airstreams separate from the backs of the blades, while the lift or torque decreases appreciably. In order to limit the power, therefore, one need only prevent the windmill from rotating in proportion to the wind speed once the maximum power has been reached. This is obtained simply by providing the generator with a compound characteristic at that point such that the power increases more quickly than the third power of the rotation speed. As a result, the speed of the windmill increases only very slowly as the wind picks up, and the power may be said to undergo no further increase, the torque becoming virtually independent of the wind speed within broad limits.

Two types of windmills have been constructed so far.

(a) Windmill with Four Blades 8 m in Diameter

This windmill is designed to produce power on the shaft of 1800 W at a wind speed of 5 m/sec, rotating at 80 rpm (peripheral speed equal to 7.5 times the wind speed). It is able to generate 10 kW at a speed of 9 m/sec, rotating at 150 rpm. Since the wind speeds for which this windmill was designed were not as high, the /121 maximum output was set at 4 kW and the normal output at 1500 to 1800 W. The blades were constructed of wood.

Each blade, of biplanar design, consists of a large vane which first receives the thrust of the wind, braced at the rear by a vane of lesser length. The two vanes are connected at various points by contoured wooden spacers. These blades have demonstrated remarkable strength during a number of accidents which occurred during the tests.

The speed multiplier with gears, the generator and the automatic brake are mounted on a cast baseplate (Fig. 80), which is able to rotate on a pivot mounted on the pylon to permit orientation.

The assembly is housed in an impervious sheet metal enclosure which is rounded in the front and terminates in a point to the rear. All the lubrication is splash lubrication, requiring no maintenance other than an oil change once a year.

Two variants of this windmill have been constructed, one on a wooden post guyed by three steel cables with a 1500 W, 24 V generator for lighting installations (Fig. 128), and the other on a metal pylon with a 1500 W, 110 V generator, for lighting and motive power installations (Fig. 80). In both cases the height of the mounting is approximately 15 m.

The weight of the mechanical part, without enclosure, is approximately 400 kg, depending on the type of generator. The blades weigh 45 kg, not including the cast hub. The generator always operates in parallel with a storage battery placed on the ground, whose capacity should be adequate to ensure operation for three days during a calm.

(b) Windmill with Two Blades 20 m in Diameter (Fig. 80)

This windmill has been designed to generate 12 kW of electricity under a 6 m/sec wind and with a rotation speed of approximately 60 rpm ($u/V = 10$). It has not been intended for use under higher winds, and the maximum output has been set at 15 kW. The blades are constructed of sheet metal, without an inside frame. Each blade consists of a large vane 10 m long, guyed by a small vane 8 m long, the two vanes being connected by contoured bracings and diagonals which operate only when the windmill has been stopped by storm winds. The multiplier and the /122 110 V generator are also connected to the top of the pylon. The total weight, not including the pylon 20 m high, is 2400 kg, the blades alone weighing 380 kg (without hub).

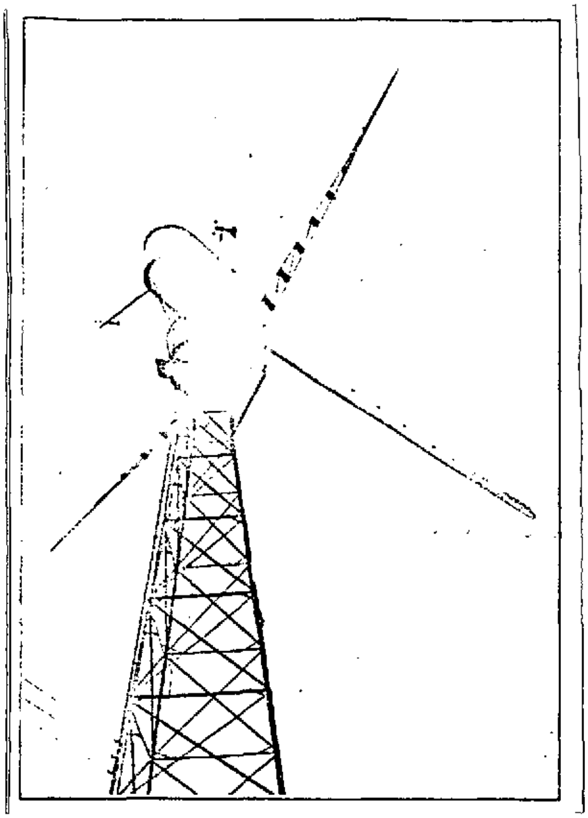


Fig. 80. Darrieus wind generator 20 m in diameter.

Test Results

The measuring devices for the two windmills, the battery and the converter unit (recording and ordinary ammeters and voltmeters, electric meters, tachymeters, recording anemometers, automatic regulators, etc.) are contained in a single box. The main problem is determination of the wind speed. The anemometer should not be placed too close to the windmill, so as to keep it out of the disturbed area, nor should it be too far away, since wind is not uniform /123 and beyond a given distance there is no longer any relationship between the instantaneous wind speed and the power of the windmill. It is, so to speak, impossible to perform instantaneous measurements, and one must therefore perform measurements extending over a given time span (a few minutes, for example), during which the average wind speed, rotation speed, output, etc., are noted.

The measurements performed under these conditions were in highly satisfactory agreement with the theoretical characteristics represented by the diagrams in Figs. 81 and 82. In particular, there was automatic power limitation for any given wind speed within a 6 to 12 m/sec range, the windmills continuing to rotate and generate their normal power even under storm winds. Useful observations were made in regard to the starting torque as well as the violent reactions provoked by the changes in orientation of the two-blade windmill. (This article appeared in the journal La Nature.)

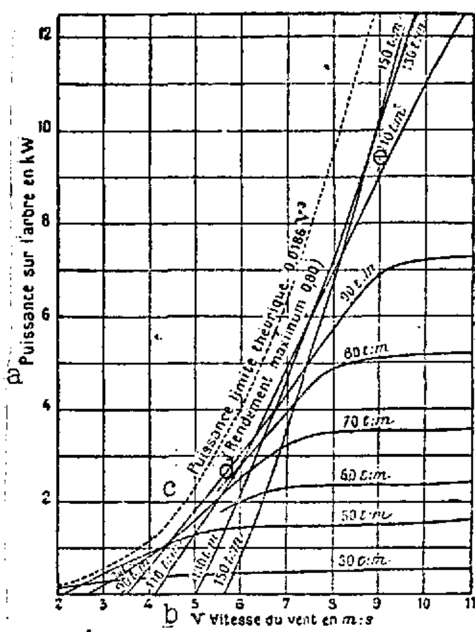


Fig. 81. Mechanical characteristics of the Darrieus windmill 8 m in diameter; mechanical power on the shaft as a function of wind speed and windmill rotation speed.

Key: a. Power on shaft in kW.
b. Wind speed in m/sec.
c. Theoretical maximum power.
d. Maximum efficiency.
e. 110 rpm (typ.).

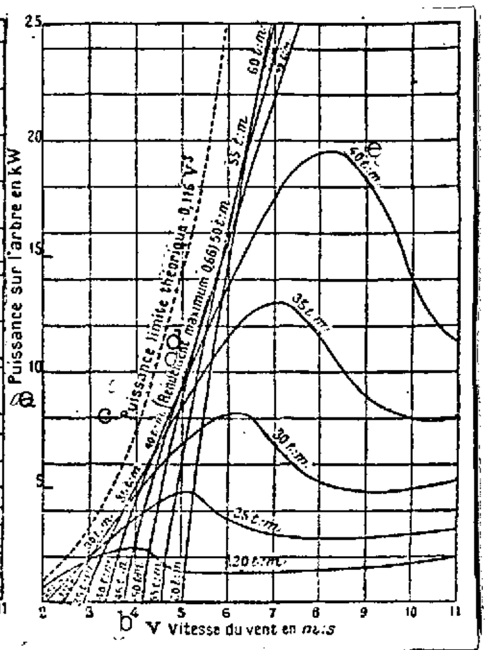


Fig. 82. Characteristics of windmill 20 m in diameter.

Key: Same as for Fig. 81, except (e), of course, is 40 rpm.

Four-Blade Airscrews with Brakes /124

The Aerodynamo Co. of Berlin uses a turbine consisting of four blades similar to those of aircraft propellers; the largest blade width is equal to approximately 1/4 the length.

Fig. 83 shows the basic design of an assembly of this type. Close to the tip of each blade is a brake consisting of a paddle p articulated on a shaft returned to idle position by a spiral spring r and resting on a stop b, as shown in drawing 3.

When the rotation speed of the wheel becomes excessive, these four paddle-brakes assume the position p' and offer resistance to acceleration of the speed of the wheel.

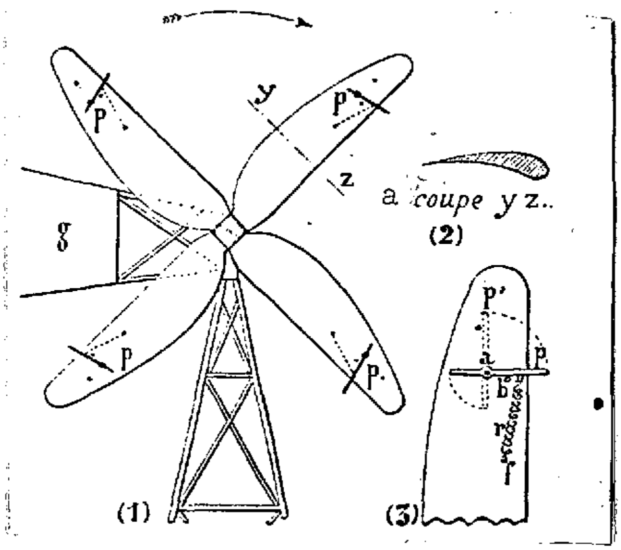


Fig. 83. "Aerodynamo" wheel (Berlin) with brakes.

Key: a. Cross section yz.

The M.A. Dumont Wind Turbine

This strange device was mentioned in the journal La Nature, No. 533, of August 18, 1883, and No. 560, of February 23, 1884, from which the accompanying illustration has been taken.

It consists of four vanes with helicoidal surfaces mounted and guyed on a horizontal shaft which in turn pivots on a vertical shaft mounted on a pylon (Fig. 84).

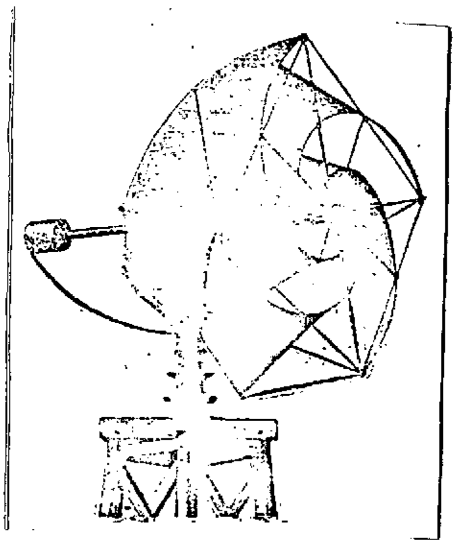


Fig. 84. The Dumont turbine.

The weight of the assembly is balanced by a counterweight. The wind strikes the helicoidal surfaces on the same side as this counterweight -- thus it would be coming from the left side of the illustration -- and the turbine orients itself in this way. According to the editor of La Nature, this turbine rotates more quickly in a low wind than in a high wind, which could be explained by the fact that a high wind is unable to pass through the windmill adequately and the air thus becomes compressed in the assembly.

In a 2 m/sec breeze the wheel rotates at a peripheral speed of 4 m, and in a 10 m/sec wind its peripheral speed is only 11 m.

This characteristic provides it with a valuable sort of self-regulation.

The motive power of a turbine of this type would be three times that of a wind wheel with paddles or vanes; this is in fact possible, since the force of the wind seems to be used more efficiently here. The angle of inclination to the shaft is 35° to 40° at the center of the vane. /126

Two of these assemblies were formerly installed in Orgelet (Jura) to supply water for the community. We have written to the mayor of Orgelet to ask what became of this installation, and he replied that it lasted only a short time because the pylon was made of wood, and if the assembly had been mounted on a solid metal pylon it might have been satisfactory,

We have been unable to locate Mr. Dumont's current address, but his design seems to us to be of considerable value, since it would be capable of yielding a higher efficiency than that of windmills with vanes. It would be necessary to obtain the necessary solidity of construction, but this does not appear to be impossible with current means.

The Sanderson Airscrew

This assembly is mentioned de Laharpe's Notes et Formules de l'Ingénieur [Engineering Notes and Formulas] as being composed of two helicoidal surfaces wound around a horizontal shaft, the inclination of the airscrew to the shaft being 45°. Thus this airscrew would be relatively similar to the Dumont turbine described above.

One of these airscrews is said to have been installed in the Villejuif reservoir (Seine), with a manual adjustment system. Another has supposedly been used by the meteorological observatory of Montsouris Park in Paris, with an automatic adjustment system. These airscrews do not seem to have been maintained beyond the test phase.

In the attempts made to capture wind power by means of airscrews, it seems unfortunate that inventors have seen no need to install their helicoidal surfaces in a sort of funnel or bellmouth, which, up to a given point, would have converted the wind speed into pressure.

This idea is mentioned in the documents given to us Mr. Bollée (see Fig. 37), but we do not know whether it has been applied, or what the results may have been.

"Pananemones"

This is the term used to describe vertical-shaft wind motors capable of turning without an orientation system under any given wind direction. The pressure of the wind can be used by no more than half of the surface area of these assemblies, and their efficiency is thus necessarily much lower than that of wheels in a vertical plane. In addition, however, the movement through the air of that part of the wheel not using the effect of the wind absorbs energy, and the efficiency thus drops to less than 20% of that of wind turbines with a horizontal shaft.

The following description of the assembly developed by Letestu is given by Professor Debauve: "Spokes positioned like the generatrices of a square-threaded screw are arranged on a vertical shaft at increasing height. These spokes are connected by an iron lattice with fairly wide openings. Rubber bands are attached to this lattice by one of their edges, and when the wind tends to press the rubber against the metal lattice, the pressure is collected and transmitted to the shaft; however, after the assembly has rotated halfway the wind comes from behind the openings and pushes back the rubber bands, which resume their normal position on the lattice and no longer transmit any pressure."

It would be useless to point out the fragility of this arrangement.

The "panemores" or "panemones" tested formerly all consisted of sails or articulated shutters assuming a position perpendicular to the wind in one semi-rotation of the shaft and in the direction of the wind during the following semi-rotation. Fragility, noise and impacts, and poor efficiency are the result.

In the Cornwall "panemone," the paddles are types of shutters mounted on a frame, becoming flattened against this frame to receive the thrust of the wind and opening when the wind is in the opposite direction. Impacts occur which may be attenuated by increasing the number of shutters. In the Lequesne and Lefèvre assembly, the opening of the paddles is limited to an angle of 70° with the tangent and the impacts are less violent as a result. In the Wood "panemone" there are several wings superposed on a vertical shaft, and a regulator varies the inclination of the paddles, depending on the speed of the assembly. /128

Other systems such as the Costes wind motor (Fig. 86) consist of concave surfaces which receive the wind during a semi-rotation and present a convex surface to the wind during the following semi-rotation. The drive power is merely the difference between the action of the wind on the concave and convex surfaces. The efficiency of this assembly is poor, despite the governing surfaces perpendicular to the concave surfaces which Costes has added to the paddles.

Another idea is to place a paddlewheel in a sort of screen which shields half of the wheel while the wind acts on the other half. Here again efficiency is poor, for the reasons given above.

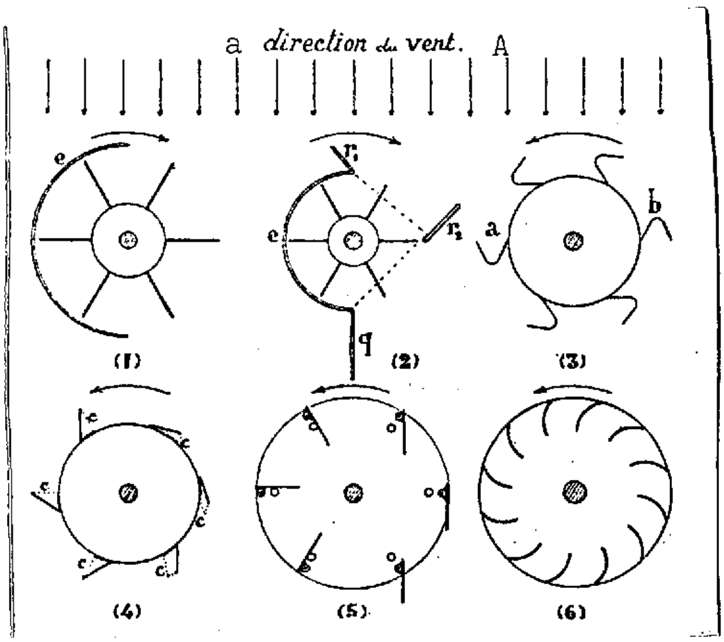


Fig. 85. Diagrams of pananemones.
Key: a. Direction of wind.

The diagrams in Fig. 85 show the principle devices which can be used to construct panemores. Here only six paddles have been included in each diagram, but obviously a larger number of paddles or buckets are used, depending on the
diameter of the assembly. /129
These diagrams are cross sections along a horizontal plane.

(1) Wheel with radial paddles, half of which is subjected to the action of the wind by a manually oriented screen or shield. e .

(2) Wheel with radial paddles with a movable shield e oriented by means of a rudder q ; two deflectors r_1 and r_2 of a piece with the screen e direct the wind onto the active paddles of the wheel. (See Fig. 92 for the design of one of these assemblies.)

(3) Cylinder with vertical troughs; the wind rushes into the concave surfaces on the one side of these cylinders and slips past the convex, "fishhead-shaped" surface on the other side. (See the Costes wind generator shown in Fig. 86.)

(4) Shutters articulated around a cylindrical surface; the opening of these shutters is limited by cables c c c, and they are turned aside from the wind along half of the circumference.

(5) Panels or shutters flexibly joined to vertical rods and stopped by fixed rods, an arrangement which turns them aside from the wind during half of one rotation. (See Fig. 91 for the design of an assembly of this type.)

(6) Curved surfaces with vertical generatrices which receive stronger thrust from the wind on their concave side than on their convex side (see the Lafond turbine). The motive power is the difference between these two diametrically opposed thrusts.

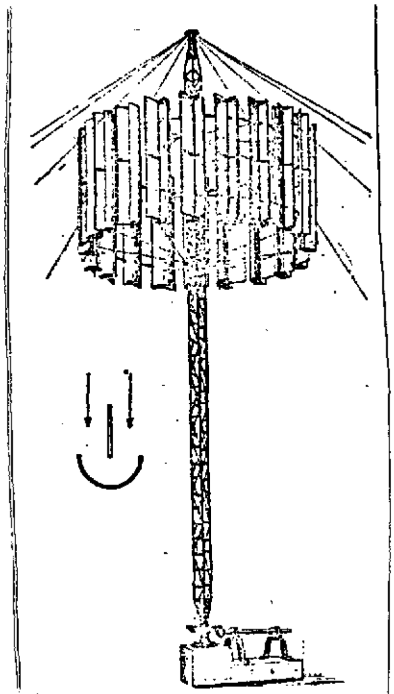


Fig. 86. Costes assembly

The Lafond Turbine (Montpellier)

This assembly consists of a cylindrical angle-iron frame with radiating shafts on which are mounted bits used to attach the vertical vanes.

A circular track on either a lower or upper platform makes it possible to transmit movement to the user equipment by friction. This is a very flexible transmission system. /130

The turbine rotates on a shaft on ball bearings (Fig. 87). It is able to start in a 2.50 m/sec wind when empty and a 3 to 3.50 m/sec wind when loaded.

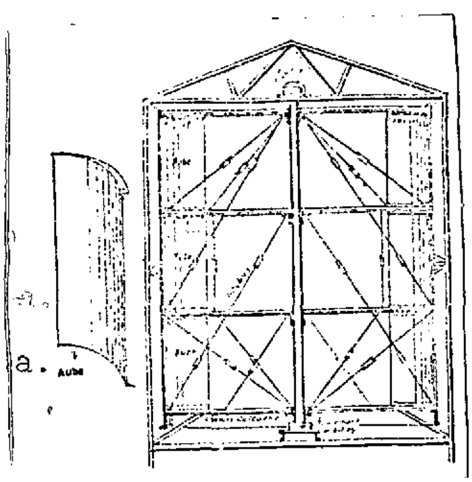


Fig. 87. Structure of the Lafond turbine.
Key. a. Blade

Fig. 89 shows how the designer is able to state that his turbine acts as a centrifugal fan above a given wind speed, permitting its use even at wind speeds of more than 15 or 20 m/sec.

Fig. 89 shows that the wind striking the concave part of the blades is deflected to the opposite blades, where it produces useful work.

The following table gives the characteristics of these assemblies and the graph in Fig. 90 gives the final performance data. /131

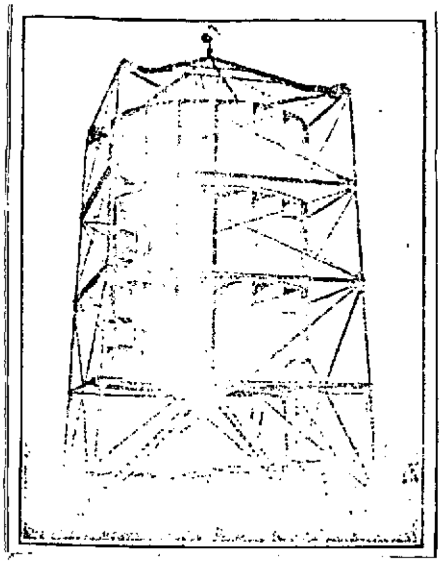


Fig. 88. Thirty square meter Lafond turbine used for irrigation. This turbine, 5 meters in diameter and 6 meters high, drives a pulley-wheel and is able to draw 80 ℓ/sec to a height of 0.30 m under a 6 m/sec wind. The elevation may be as high as 0.70 m when the wind speed reaches 80 m/sec.

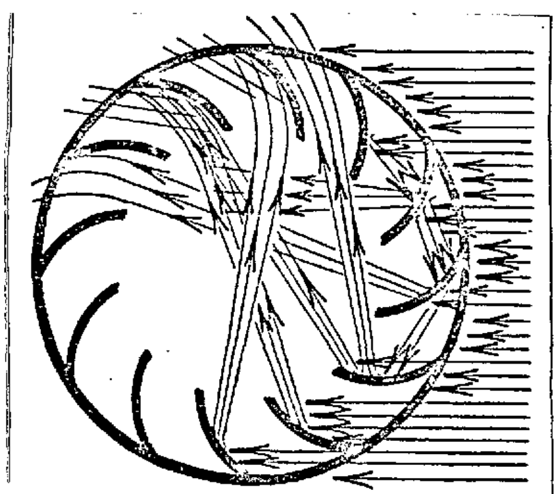


Fig. 89. Airstream paths in the Lafond turbine.

Structure of a Pananemone with Oscillating Shutters

This assembly consists of a sort of large round cage rotating on a vertical shaft; large wooden shutters or panels covered with stretched canvas, which receive the thrust of the wind, are articulated on the vertical rods of this cage (Fig. 91). Drawing 3 shows this cage seen from above; it is a double row of vertical rods t, positioned on two concentric circles; each of the 12 panels p is articulated on one of the vertical rods and is stopped by the other.

From drawing 3 it can be seen that the wind, moving in the direction indicated by the arrows, pushes against the panels marked 1, 2, 3, 4 and 5, i.e., for slightly less than half a rotation of the cage. The wind does not act on panels 6 and 12, which are in the plane of its direction; panel 7 is pivoted on its shaft under the thrust of the wind and is turned aside from the wind, as are panels 8, 9, 10 and 11, which remain turned aside until they have gone past position 12. After this point the wind strikes them once again.

Obviously this assembly is able to operate independently of wind direction.

The motive power which can be supplied by this pananemone depends on the wind speed and the area of the movable panels. /133

If one of these assemblies were to be used, for example, to drive a pump drawing water from a well to a height of 15 m from the water level in the well to that in the upper tank, in a quantity of 1-5 m^3/hr, varying with the wind speed, the rotating cage could be given a diameter of 2 m and a height of 2 m. Each panel would thus be approximately 2 m high and 0.50 m wide, with an area of 1 m^2, and 10 to 12 panels would be

CHARACTERISTICS OF THE LAFOND WIND TURBINES

Area in m^2	Shaft power at wind speeds of:			Rpm with load at wind speeds of:				Diameter	Height	Number of stages	Number of blades	Blades	Total approximate weight of turbine	Weight of a pylon 4 m below the turbine
	4.5 m	7 m.	10 m.	4.5m	7 m.	10 m.	Maximum							
4	4.7 kgm.	14 kgm.	40 kgm.	17	26,5	38	120	2 m.	2 m.	2	24	0.50 m x 1 m	600 kg.	1,200 kg.
6	7 kgm.	21 kgm.	60 kgm.	»	»	»	»	»	3 m.	3	36	»	800 kg.	1,350 kg.
8	10 kgm.	28 kgm.	1.10 hp	»	»	»	»	»	4 m.	4	48	»	1,000 kg.	1,500 kg.
16	19 kgm.	56 kgm.	2.15 hp	8,6	13,2	19	60	4 m.	4 m.	2	24	1 m. × 2 m.	2,000 kg.	2,000 kg.
24	28 kgm.	1.10 hp	3.20 hp	»	»	»	»	»	6 m.	3	36	»	2,800 kg.	2,500 kg.
36	42 kgm.	1.65 hp	4.80 hp	5,7	9	12,8	40	6 m.	6 m.	3	54	»	4,800 kg.	3,800 kg.
60	70 kgm.	2.75 hp	8 hp	»	»	»	»	»	10 m.	5	90	»	7,200 kg.	6,000 kg.

/132

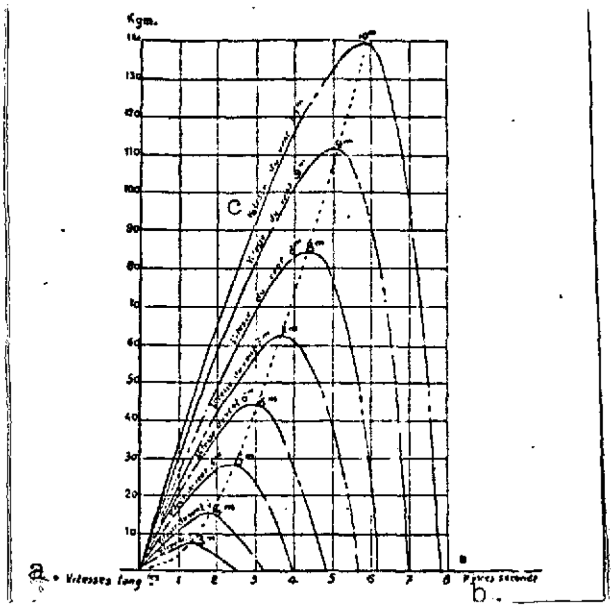


Fig. 90.
Key. a. Tangential speeds
b. M/sec
c. Wind speed (typ.)

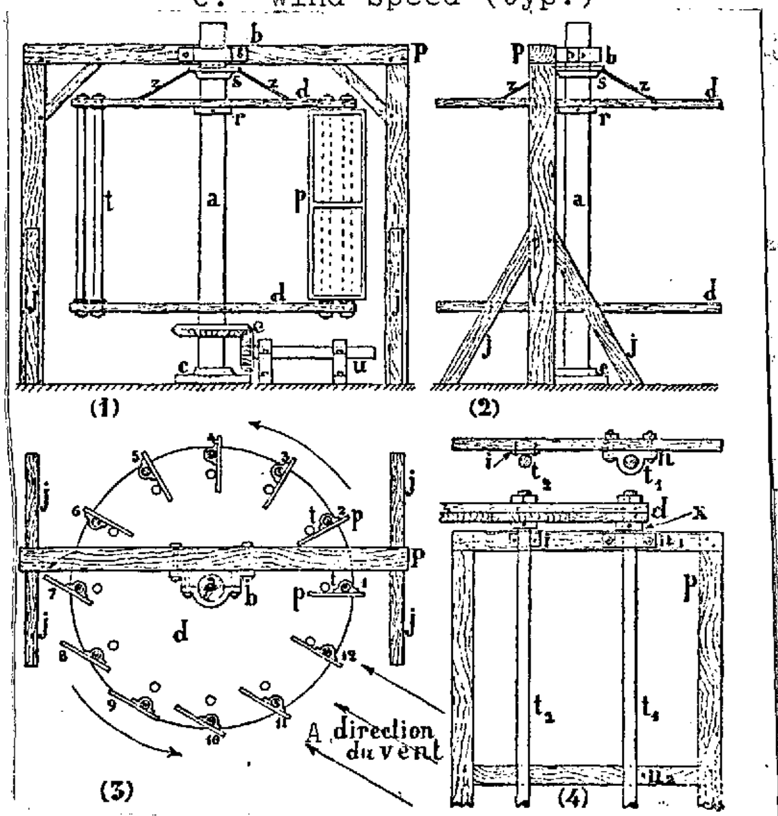


Fig. 91. Panemone with oscillating shutters. Key. A. Direction of wind

placed around the circumference of the rotating cage. Fig. 91

The structure of the assembly includes:

1. A solid gantry P, shown from the front (Drawing 1), in profile (Drawing 2) and from above (Drawing 3). This gantry, similar to a gymnasium cross-beam, must be firmly braced by struts J J, with solid concrete bases for the ends of these /134
struts as well as the supports of the gantry. For optimum stability, other struts should be added outside the supports, within the plane of the gantry, but these have not been shown here.

This gantry may be constructed of oak beams or steel girders.

The rotating cage is mounted on a vertical shaft a, resting in a center-casting c at the bottom and held in place by a vertical floor-bearing b at the top.

Two disks dd are keyed into thick sheet metal plates on this vertical shaft. Each of these disks may be constructed of two fir planks nailed together against the grain as may be seen in d (Drawing 4).

Steel rods t are secured between the two disks dd (Drawings 1 and 3) in two rows 15-20 cm apart. Fig. 4 shows a detail of the attachment of these rods, by means of a ring x and a nut, between which the disk d is fastened. These rods are assigned a diameter of 20 mm. If the disks d are large enough, more than 2 m in diameter, it is useful to support the upper disk with tie-rods zz attached to a large keyed washer at the top of the vertical shaft a.

To the base of this shaft a is keyed a toothed wheel which meshes with a pinion driving a horizontal shaft u; to this shaft can be attached a pulley which will receive the control belt from a pump or any other machine.

3. The movable panels will be constructed of good-quality fir, without damaging knots, in planks 7-8 cm wide and approximately 4 cm thick, pinned with mortises and tenons, with one or several intermediate cross-beams, depending on their height.

The number of these panels to be mounted on the circumference of the disks dd will obviously vary according to the diameter of these disks and according to the width of the panels. In any case there must be adequate space between two panels so that one panel is able to rotate a half-turn without catching on a neighboring panel, as is the case during a change of position by panel 7 (Drawing 3).

Drawing 4 shows a structural detail of one of these panels p: its articulation with the rod t_1 consists of bronze mountings n_1 and n_2 which are in wide commercial use (see the catalogue of the Piat Foundaries in Paris). These mountings are sold reamed with openings of any diameter (only mounting n_2 is shown in our drawing). /135

As it pivots, the panel somewhat forcibly strikes the second rod t_2, which serves as a stop. This impact is damped by nailing a fairly thick sheet of rubber or felt to the panel (pieces of old inner tubes from automobile tires).

The panels p thus consist of wooden frames which must be covered with strong canvas of the quality used for sails or awnings. It is a good idea to attach these sections of canvas to their frames by cords, studs or fasteners, so that they can be removed in the case of a heavy storm or heavy storm warning, in which the excessive wind might damage the pananemone.

Another possibility for protection against storm winds is to provide a system for securing movable panels against the stop rods (t_2 in Drawing 4). In this way the panels will no longer be able to pivot on the rod t1 and the thrust of the wind will be balanced on each side of the cage, which will no longer rotate. Nevertheless, it is more advisable to take down the canvas completely.

If one wishes to build a pananemone of large dimensions, with a cage height of more than 2.50 m, for example, this cage must be divided into two stages by placing a third disk d between the two shown in Drawings 1 and 2. The panels p will thus be smaller, easier to cover with canvas and easier to maintain than extremely large panels.

<u>Design of a Pananemone with Shielded Paddles</u>

If we consider a paddle wheel (Fig. 92, Diagram 1) mounted on a vertical shaft and exposed to wind as indicated by the small arrows, it is obvious that the pressure of the wind will be the same on paddles p_1 and p_2 on either side of the vertical shaft, and that the wheel will not turn. However, if we obstruct the thrust of the wind on one half of the wheel by means of a sort of screen (Diagram 2), the thrust of the wind will have an effect only on paddles p_1 and the wheel will turn in the direction of the arrow, even though the direction of the wind will remain parallel to the diameter of the screen e.

Since wind direction varies frequently, it is necessary to shift the screen e appropriately so that its diameter will remain in the direction of the wind and the wheel will continue to rotate.

This movement of the screen e may be performed by hand, as was the case with the orientation of the old windmills, which had to be watched constantly by the miller to keep the blades facing into the wind.

However, it is easy to construct an automatic orientation system for our assembly by installing the screen e on a pivot /136
concentric to the vertical shaft of the wheel and by equipping this screen e with a rudder q which will keep the diameter of the screen in the direction of the wind. A basic diagram of this design is shown in Diagram 3.

In this assembly, it may be seen that the screen is on only one side of the central shaft, with extremely poor balance as a result, all the weight being on one side of the pivot. We will improve this balance by installing a second screen d (Diagram 3) which will serve as a deflector and will direct the wind onto the paddles p_1, which will receive a more powerful thrust in this way.

The thrust of the wind on deflector d balances the thrust on the fixed surface of the screen e, which helps to improve the static balancing of the assembly as a whole.

Diagrams 4 and 5 show one type of design for this wind motor. Diagram 4 shows a cross section along a vertical plane

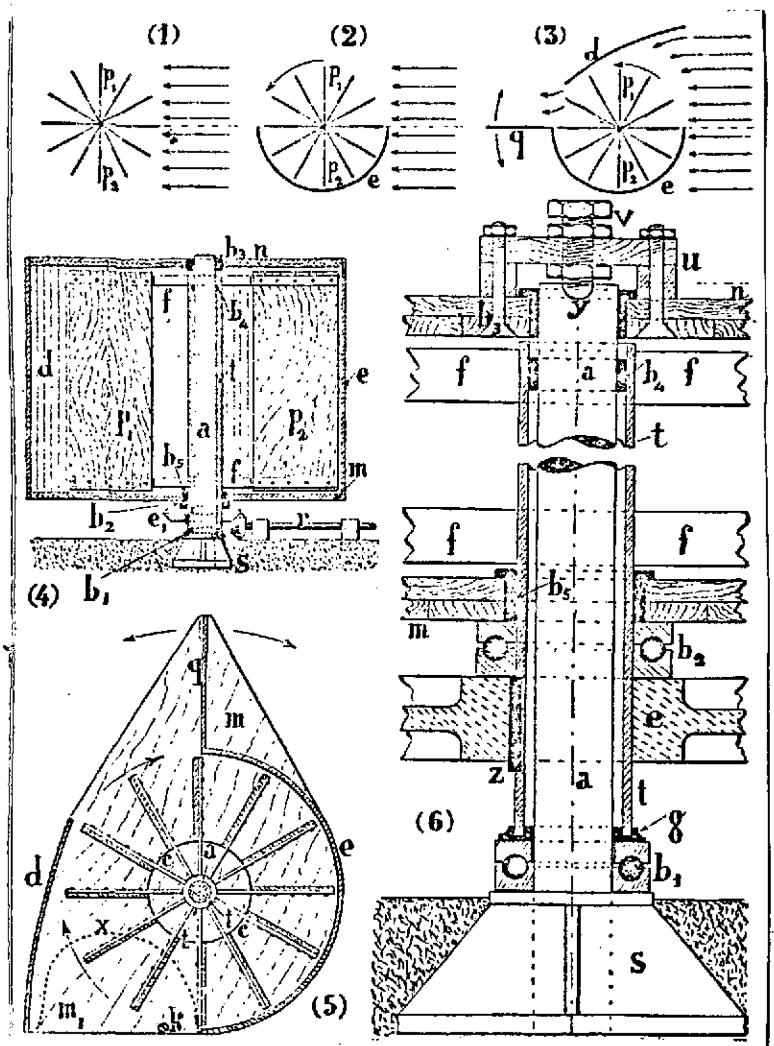


Fig. 92. Panemone with automatically shielded paddles.

passing through the vertical shaft, and Fig. 5 a cross section along a horizontal plane halfway up the assembly.

An extremely rigid steel, iron or cast metal vertical shaft is embedded in concrete or firmly secured to a frame. The present diagram shows a cast metal shoe s receiving the base of the shaft a and embedded in concrete. Any method may be used to secure this shaft a, however. For example, one can use cross-girders and oblique struts, a procedure often used to secure the base of a post or pole with a free top end firmly onto a buildings or frame pylon. Into this fixed shaft a is inserted a steel tube t which is able to rotate freely on the fixed shaft a. The base of the tube t should rest on a thrust-bearing b_1 which supports the entire weight of the moving parts of the wind motor. Diagram 6, which shows the structural details of the shaft a and the pivots of the moving parts, also shows a thrust ball bearing b_1 at the base of the hollow shaft t. This thrust ball bearing is obviously much preferable to friction on washers made of bronze or any other metal.

The top of the hollow shaft t should be equipped with friction lining b_4, for its rotation on the fixed shaft a. Here we have shown a complete ring b_4 (Diagram 6), but a ball bearing would be much preferable, and should be used when the diameter of the hollow shaft t permits.

A toothed wheel e_1 (Figures 4 and 6) is keyed to the bottom of the hollow shaft t. This wheel transmits the power of the assembly through a bevel gear to a horizontal shaft r, which is used to drive a pump, a generator or any other type of equipment.

To the hollow shaft t are attached arms ff which support the paddles of the drive wheel. The number, width and height of these paddles may vary according to the output desired; six paddles will be used if the diameter of the wheel is only 1 m, nine paddles for a diameter of 1.50 m, 12 paddles for a diameter /138
of 2 m, and so on, so that the distance between the tips of two consecutive paddles should be between approximately 50 and 70 cm.

The arms ff may be attached to the hollow shaft t by thick sheet metal washers keyed or bolted onto the hollow shaft by means of iron angle brackets. It must be possible to disassemble these arms if necessary, since the platform supporting the screen e must be installed prior to the paddle wheel, as we will see shortly. The paddles will be constructed of thin planks or sheet metal.

To give the paddle wheel sufficient strength, the arms ff will be firmly joined by means of iron rings cc (Diagram 5); the tips of the paddles may even be connected by strip iron rings (flat, narrow iron). The screen e, the deflector d and the orientation rudder q are mounted between two wooden or sheet metal platforms mn equipped with angles (Diagram 4). Diagram 5 shows the approximate form of the lower platform m; the upper platform n should have the same form, but it is useful to make wide indentations on the side from which the wind enters the wheel, along the curve indicated by the dotted line m_1 x k (Diagram 5), to facilitate the action of wind attacking the paddles at a steep downward angle.

Point k indicates a more or less heavy weight designed for static balancing of the screen, deflector and rudder assembly around the central shaft.

The lower platform m of this wind-governing assembly rests on a thrust washer b_2 and is able to rotate freely on the hollow shaft t due to an interposed thrust ring b_5. For the bearing b_2, Diagram 6 shows a ball bearing, which is preferable to a smooth washer.

The upper platform n rotates freely around a central main shaft a by means of a thrust ring b_3.

Rings b_3 and b_5 (Drawings 4 and 6) may be advantageously replaced by ball bearings.

The drawback of this system for mounting the orientation device is that its weight drags on the hollow shaft of the paddle wheel, producing a braking effect which detracts from the efficiency of the mechanism.

To eliminate this braking effect, the weight of the screen e, the deflector d and the rudder q is supported by a stop screw v, above the shaft a, which does not rotate. The screw /139
v, adjusted by two nuts (Diagram 6), rests in a cavity y forming a socket at the top of the central shaft a, which thus supports the entire weight of the accessory screen and orientation system.

The platforms m and n, between which the screen e, the deflector d and the rudder q are secured, may be constructed of planks 2½ cm thick, nailed against the grain as we have shown in Diagram 6, as long as the diameter of the assembly is no more than 2 m. With larger diameters these platforms must be equipped with a central cast metal washer or with angles in order to maintain their rigidity against the weight they are supporting.

The surfaces making up the screen, the deflector and the rudder will consist of thin laths or sheet metal, or zinc approximately 0.5 mm thick, depending on their surface area. The entire system will be given two or three coats of carbonyl or oil-base paint to prevent rotting and rust.

All rubbing parts, bearings and bearing races b_1, b_2, b_3, b_4 and b_5 should be well lubricated. This is the only maintenance necessary for this assembly; in view of the slow relative speed of the moving parts, thick oil or consistent grease should be used for lubrication.

The dimensions of these assemblies remain to be considered. These depend on the output needed and the force of the wind in the region involved. The output of a wind motor is extremely variable, depending on the force of the wind; here we will merely indicate the dimensions necessary to drive a water pump drawing approximately 5,000 l/hr or a small generator requiring no more than one horsepower. For these purposes, the central shaft a should be 2-3 m high, depending on the degree of exposure to the wind, and the drive wheel will be given a diameter of approximately 2-3 m so as to obtain an assembly whose vertical cross section (Diagram 4) is almost square, roughly as wide as it is high.

CHAPTER VIII. TRANSMISSION OF POWER FROM WIND MOTORS TO USER EQUIPMENT /140

Three methods are used: by vertical rod, by vertical rotating shaft, and by electricity, the generator being placed at the top of the pylon in the latter case.

1. Transmission by Vertical Links and Rods

The wind wheel may be mounted on an inset shaft, a shaft supporting a platform with a crankpin, or an excentric shaft. Power is transmitted directly from the main shaft of the wheel to a link which is hinged to a rod extending the piston rod of the pump.

This system has the advantage of extreme simplicity, but the drawback of loading the crank, and as a result, the wind wheel, with the considerable weight of the rod and the link during one half-turn (ascent of the link), with this same weight tending to pull the wheel during the following half-turn.

This makes it extremely difficult to start the windmill if the link is at the end of its low stroke. This is almost always the case when the windmill is about to start, making it impossible to bring the assembly into operation under low winds.

This drawback may be corrected by attaching a lead or cast metal counterweight to the circumference of the paddlewheel opposite the crank. The weight of this counterweight may be as high as 50 kg when the link is extremely long. For example, in an installation with a pylon 20 m high and a well 30 m deep--dimensions which frequently occur--the rod extends the piston rod of the pump to a length of more than 40 m and weighs 200 kg or more. This gives some idea of the counterweight required.

The most serious problem, however, is that the presence of this counterweight on the wind wheel causes dynamic unbalancing which may detract from the sturdiness of the wheel when it is /141
rotating at high speeds.

Better results may be obtained by the more rational method of using two or three links and rods acting on two or three pumps. In this case, static balancing may be obtained on the main shaft alone with no detracting effect on the dynamic balancing in view of the low angular speed of this shaft.

For the reasons given above, transmission by a single vertical rod can be used only with small-diameter wind motors (wheel diameter of less than 5 m) mounted on relatively low pylons with the pump at the foot of the pylon. Thus the rod used in these assemblies would be relatively light.

Figure 34 shows a Halladay-Shabaver windmill with a platform with a keyed crankpin at the end of the main shaft of the wheel. The link, which is made of wood, is articulated with the steel rod R at r'.

In the Chêne [Oak] wind generators a bent shaft is used.

Finally, the Lykkegaard Company uses an eccentric, as shown in Fig. 93. The connecting-rod of the eccentric is cross-braced and articulated with a steel rod guided by a slider.

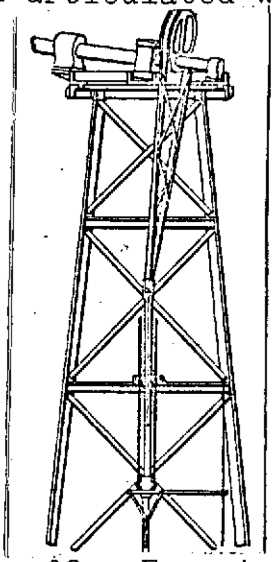


Fig. 93. Eccentric manufactured by the Lykkegaard Company.

A transmission system consisting of gears in an oil bath in a closed gearbox between the main shaft of the wind wheel and the crankpin of the big end of the connecting rod is used by a large number of designers. Generally, the spur gear train reduces the ratio between the wheel and the crankshaft. As a result, the crankshaft makes only a single rotation as the paddle wheel rotates two or three times. This considerably facilitates starting under low wind.

In the mechanism designed by Chapuis (the Aiglon Windmill, Fig. 94), only one pair of gears is involved; in that of Gold Shapley and Muir of Brantfort (Canada) (Fig. 95) there are two pairs of gears, completely balancing the stresses, which are contained in a watertight gearbox with oil bath. The large end of the connecting rod /143
is driven by a crankpin directly keyed to the two large gears.

The Star windmill of Flint and Walling Company of Kendallville, Indiana, has two pairs of reduction gears and a vertical rod activated by two small rods and an oscillating transverse butt which may be seen in front and side views in Fig. 96. Lubrication is provided by extremely large oil cups. Fig. 97 shows a few structural details of this assembly.

The Cyclone wind generators in Compiègne, Oise, whose wheels are 2-5.50 m in diameter, use a system of reduction gears with a ratio of 1:3 (approximately) and two connecting rods on a double gear train.

The pump rod is guided by two vertical steel slides.

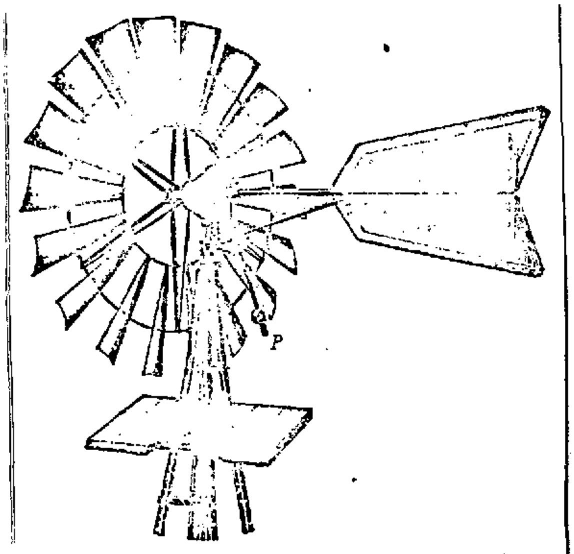


Fig. 94. Mechanism of the Aiglon windmill

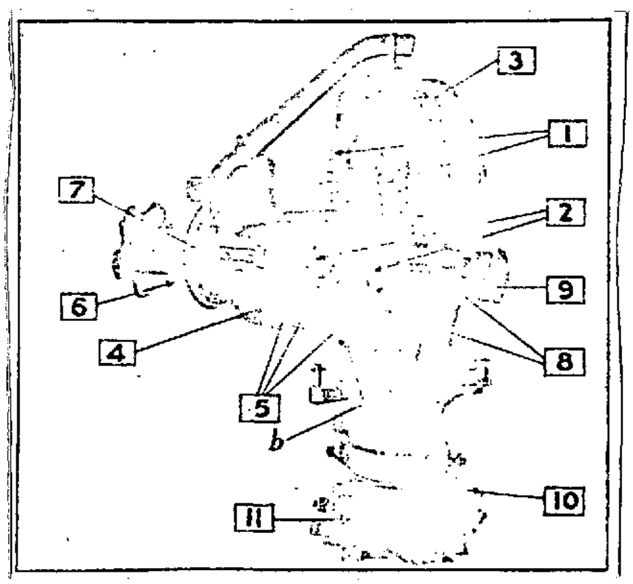


Fig. 95. Mechanism of the Gold Shapley and Muir assembly. Key. 1. Large toothed wheels driving the connecting-rod; 2. Gears keyed to the shaft of the windmill; 3. Large end of connecting-rod b; 4. Gearbox with oil bath (the top of the gearbox is cut away to reveal the mechanism); 5. Lubricating rings; 6. Steel band brakes for stopping the windmill; 7. [key continues next page]

The gears, connecting rods and bearings are constantly fed by an oil bath. A special system for raising oil by an endless chain insures lubrication of all mechanisms positioned above the level of the oil.

For windmills with a diameter of 6.50-7.50 m, this firm uses a single connecting-rod without reduction gears. /144

The crankshaft is keyed into the hub of the drive wheel; this arrangement may be used for large-diameter assemblies whose rotation speed does not exceed 25-28 rpm.

An adjustable counterweight positioned on the arm opposite the crankpin of the crankshaft is used for balance and smooth starting.

This adjustable counterweight is provided to counterbalance the weight of the rods and part of the weight of the water.

As in the other types of assemblies, lubrication is provided by an oil bath and an endless chain.

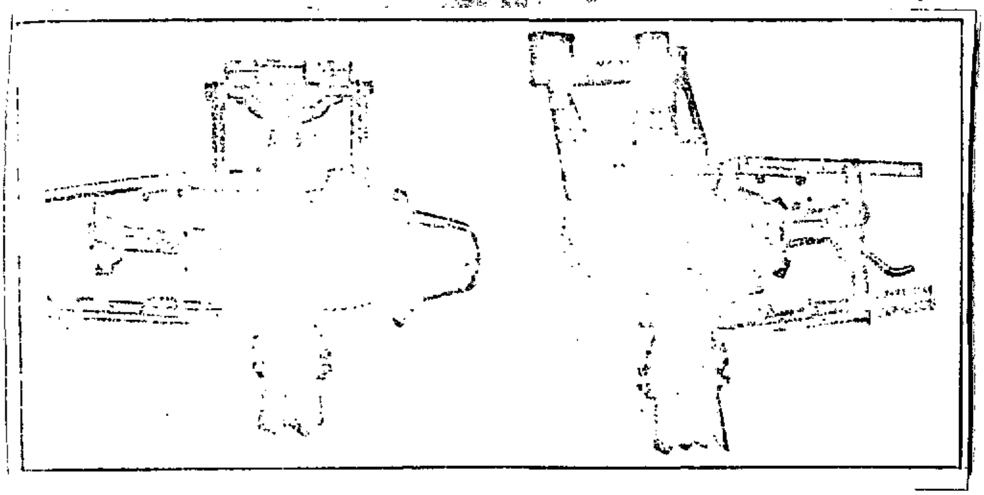
Gold, Shapley and Muir of Brantfort, Canada, use a simple inside gear, as shown in Fig. 99, for transmission in small wind motors with wheels only 2.45 m in diameter. The speed of the /145 wheel, considerably reduced by the inside gear, is transmitted by a connecting-rod b above the pump rod, which is merely guided by a cylindrical slide. The lubrication is provided by large oil cups. A brake f is

[Fig. 95 key, cont'd:]
7. Thrust ring receiving the thrust of the paddle wheel; 8. Roller bearings; 9. Cap of gearbox; 10. Ball bearing for orientation; 11. Cap covering pylon.

added to the mechanism, and may be activated by a cable from the bottom of the pylon (Fig. 98).

The Aermotor Company of Chicago (Leclercq and Jarre in Paris) reduces the gear ratio by means of two pairs of spur gears with oil bath, which transmit motion to the large vertical rod by two connecting-rods and a cross-rod guided by a grooved roller in a vertical slide in the form of an inverted U. The mechanism is covered by a large galvanized steel hood.

This mechanism is shown in Fig. 100. The oil tank has been made transparent to reveal the gears, and the same is true of the upper hood, through which the connecting-rods and slide can be seen. One advantage of this design is that the thrust given to the vertical rod is absolutely straight. Fig. 100 shows the outside view of this drive head, and Fig. 101 a diagram of the mechanism. /146



Rigged into the wind. Rigged against the wind.

Fig. 96. Pumping mechanism manufactured by Flint and Walling.

The diagram (Fig. 101) shows how the large toothed gears turn in the direction indicated by the arrows z, with the result that the connecting-rods c are parallel to the rod i of the pump during the ascending stroke of the piston. /147

German windmills use the same type of mechanism as American windmills.

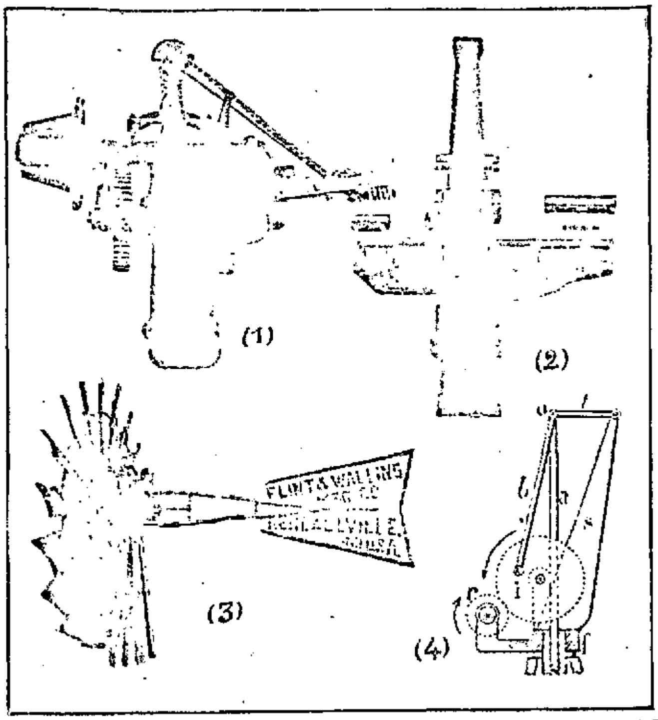


Fig. 97. Mechanism manufactured by the Flint and Walling Company. Key. 1. Top view; 2. View of head serving as a pivoting mounting; 3. View of assembly rigged into the wind; 4. Diagram of mechanism: f. Base and head of pylon; r. Shaft of wheel and drive gears; i. Reduction gears; b. Double connecting rod; a. rod of pump; o. Attack cross-beam of connecting-rods; t. Oscillating guiding beam; s. Mounting.

Lubrication

All designers are concerned with this problem, and some windmill heads have cups or gear-boxes containing enough oil so that there will be no need for replenishing for at least one year. This is extremely important, since the task of ascending the pylon and lubricating the parts requires a worker who is a good climber.

Structure and Guidance of Rods

The vertical rod positioned within the axis of the pylon consists of steel tubes connected end-to-end by threaded sleeves or firmly pinned inside cylinders, or Northern fir wooden tubes 60 or 80 millimeters square, their successive lengths being connected by flat steel splice-pieces bolted onto the wood.

The round steel rods are guided through either slides or grooved rollers; the wooden rods are guided by cylindrical rollers, or the components are connected by round steel parts guided as described above.

Theoretically, the rod must not operate under compression, since this would be bound to curve it due to its extensive length. The heaviest stresses should occur as the rod is ascending. The guiding rollers are generally mounted on ball bearings.

Hérisson Transmission

So that all the available wind power is used, the strength of the user equipment must increase as the wind speed increases.

In regard to piston-driven pumps, to achieve this goal Hérisson recommends the use of the device shown by the schematic diagram in Fig. 102. /148
Here the stroke of the pump piston varies automatically with the wind speed.

For this purpose, the rod t of the wind motor attacks the pump by means of an equalizing-bar u and a lever v hinged at a fixed point i. A slide c permits the lower end of the equalizing-lever u to slide along the lever v.

This equalizing-lever u is in addition joined to a connecting-rod b which in turn is connected to a vertical lever l, joined at a to a bracket of one piece with the pylon. The upper end of this vertical lever l is equipped with a rigid plane e exposed to the wind. When the wind speed increases, the screen e tilts the lever l and the slide c approaches its point of articulation i; in this way the stroke of the piston p is increased.

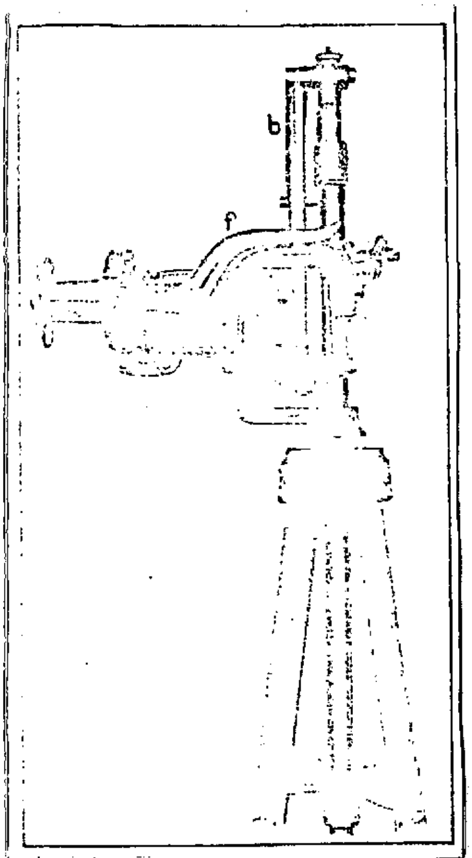


Fig. 98. Gold Shapley and Muir mechanism for small windmills.

When the wind speed decreases, the slide c is pushed to the rear by a counteracting spring s and the stroke of the piston decreases.

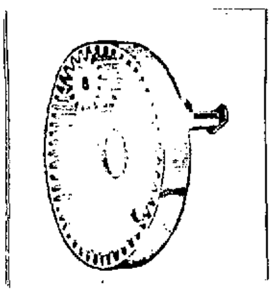


Fig. 99. Reduction gear.

To balance out the weight of the rod t and the stresses on the piston of the pump, which are unequal during aspiration and delivery, Hérisson proposes connecting two strong springs rr between part d of the upper platform of the pylon and the rod t. These two springs would store a part of the energy during the descent of this rod and would resore it as the rod reascends.

Case of a Pump Not Installed Beneath the Pylon

Here the transmission must be combined with reciprocating motion at a distance. This may be obtained in various ways:

1. Fig. 104. The transmission consists of two bell crank levers s_1 and s_2 and a rigid rod u. If this rod, which may

consist of an iron or steel tube, is very long, it is supported by one or several grooved pulleys or rollers g.

2. Fig. 103. The transmission consists of a flexible hemp or steel cable or a chain kk attached to the base of the rod t of the windmill, passing over a return-pulley r_1 to drive the pump by a bell crank lever s. This lever s has a counter-weight c_1 which furnishes the descending stroke of the piston p, with the cable kk acting only during the ascending delivery and aspiration strokes. /149

A cable is attached to the bottom of the rod t to balance the weight of this rod and that of the counterweight c_1. This cable passes over a pulley r_2 and bears a second counterweight c_2 appropriately dimensioned to equalize the stress during the descent and ascent of the rod t.

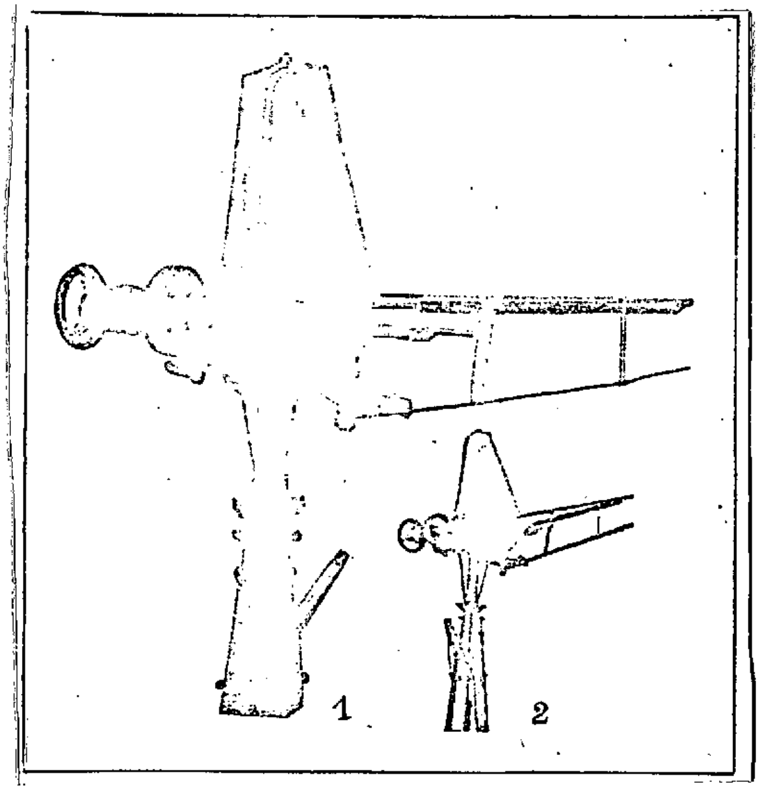


Fig. 100. Mechanism of the Aermotor.

3. Fig. 105 (1). This transmission system consists of T-shaped levers, each oscillating around a fixed point $l_1 l_2$ and connected by high-tension steel cables or by rigid rods joined to suspension points. The horizontal branch of the lever l_2 is placed to the right or the left of the vertical branch, depending on whether the reciprocating motion of the receiving rod p is to match or be in opposition to the motion of the drive rod t. If the levers $l_1 l_2$ are connected by cables, the latter must be equipped with some type of system to adjust their tension, since if these cables are lax the motion of the assembly will produce jerks which are likely to cause damage.

Figure 105 (2) shows that this system with levers and cables may be used to transmit motion in any given direction by means of return-pulleys r. /150

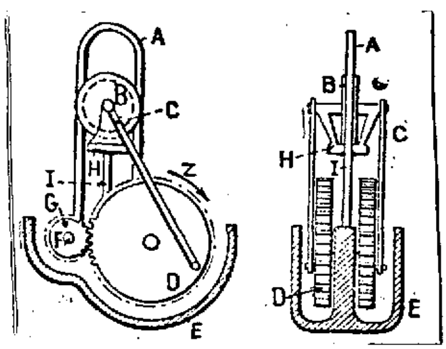


Fig. 101. Diagram of the Aermotor. Key. a. Guidance system; b. Guiding roller; c. Connecting-rods; d. large gears; e. Gear-box with oil bath; f. Shaft of wind wheel; g. Small gears; h. Cross-head; i. Vertical rod connected to pump piston.

4. Fig. 105 (3). Transmission by rollers and rods (Gould) system). Grooved rollers rrr roll between two suitably curved rails aa and are connected by articulated rods. The drive rod t and the receiving rod p are each guided by rollers gg whose shafts are fixed in relation to the rails aa. This type of return may be obtained in a horizontal, vertical or oblique plane.

2. Transmission by a Vertical Rotating Shaft.

This mode of transmission between the wind wheel and the user equipment has a number of advantages over the vertical rod system. It makes it possible to:

--give the main shaft of the paddlewheel an inclination of approximately 15° from the horizontal, which, according to the most reliable sources, is advantageous for satisfactory use of the wind, as shown in Fig. 44 (Danish Agricco windmill); /151

--multiply the low speed of the windmill by the use of a single bevel gear train; the rotation speed of the vertical shaft can be increased as much as possible for improved energy transmission;

--to place the gear train and the bearings of the shaft in a single small, light and completely watertight gearbox with oil bath. Fig. 50 shows this gearbox, seen in cross section, on a large Danish Mammouth windmill.

Guidance and support of the rotating vertical shaft are easy to obtain by means of vertical bearings with oil bath or ball bearings spaced 3 or 4 m apart, as represented by bbb in Fig. 106. The bottom end of the vertical shaft rests and rotates in a socket with oil bath, or, better still, in a strong thrust bearing.

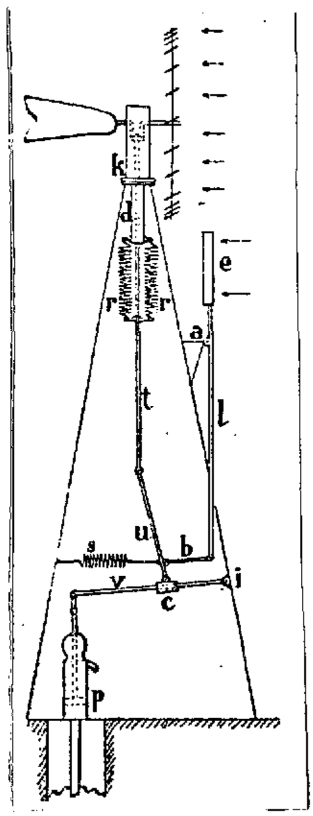


Fig. 102.
Hérisson
transmission.

Rotating shafts are used only with large wind generators (wheels more than 6 m in diameter). This type of shaft is constructed of solid steel or drawn steel tubes with the diameter broad enough to prevent excessive bending due to its considerable length and the relatively low speed (2 or 3 times that of the wind wheel). In large windmills, the shaft will transmit power as high as 60 hp, and it should therefore be dimensioned with care.

Fig. 106 is a schematic diagram of the /152
application of a rotary transmission to various uses. One or several bevel gears e_1e_2 are positioned towards the base of the vertical shaft; these may be engaged or disengaged at will by clutch couplings c_1c_2. These couplings transmit motion to horizontal shafts driving a pump P. Also mounted on these horizontal shafts are pulleys p, p_1, p_2 and p_3, one of which controls a generator, and the others various types of farming or other equipment as needed.

Mr. Laurent, of the Etablissements Chène
in Saint-Quentin, has made it possible for us /153
to visit the installation set up by Mr. Pottier in Maurecourt (Aisne). Here a wind wheel 4.50 m in diameter is supplying water, electric lighting and drive power for all the farming equipment; grain sorters, root-cutters, threshing machines, etc. Obviously these machines are not all in operation at the same time, but this small windmill has been adequate to meet all the farm needs. The transmission system is roughly as shown in Fig. 106.

Fig. 107 shows an installation set up by Athlet Herzogs, a /154
German company, for various agricultural uses; the pylon rests on the first floor of the building.

Fig. 108 shows two large Danish Mammouth windmill installations. In the one on the left, the generator B is driven directly by gears housed in an oiled gearbox A whose structural details are shown in Figs. 109 and 110. All the shafts are mounted on bearings and thrust bearings with double rows of balls; this careful construction is quite unusual and yields better efficiency. In these two installations the vanes of the windmill can be turned aside by means of a lever C located in the engine room; the lever is connected to the vanes by a cable and return-pulleys.

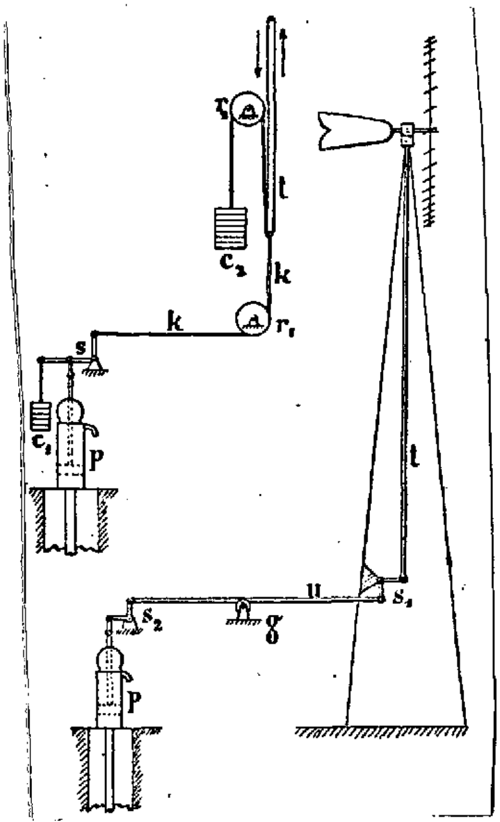


Fig. 103 (right). Transmission by bell crank levers. Fig. 104 (upper left). Transmission by cable.

Fig. 111 shows two types of gear movements used at the base of the pylon (Construction Durey-Sohy). The shaft of any type of machine can be connected to these return-gears, which may multiply or reduce the rotation speed of the vertical shaft of the wind motor. A pulley may also be keyed to these gears for transmission by belt or teledynamic cable. /155

Fig. 112 shows the bevel gear boxes designed by F. Kösser.

Figs. 158, 161 and 165 show the application of vertical shaft motion to a two-chambered pump, a noria and an Archimedes' screw.

In Remigny (Aisne), we have seen an Hercule wind motor (Chêne, Saint-Quentin) mounted on a reinforced concrete pylon 26 m high drawing water from a depth of 30 m with a three-chambered pump driven by a vertical shaft and gears, for the community public water supply. There are a number of these installations currently in France and a great many more in other countries.

The Cyclone wind motor company of Compiègne have sent us photographs of their rotating vertical shaft transmission system. Fig. 115 shows the head of the assembly with the shaft of the wheel at an angle with the horizon. The gears are completely enclosed in an oil bath and a small pump on the top end of the vertical shaft draws the oil up through two tubes. Fig. 116 shows the gearbox with oil bath at /156
the base of the pylon. This cast gearbox is bolted onto a cast bed-plate sealed into the foundations, which allows easy and accurate setting of the gearbox in order to straighten the vertical shaft.

All the shafts of these two assemblies are mounted on ball bearings, as may be seen in Figs. 113, 114 and 115.

Windmills with vertical rotating shafts are well suited to

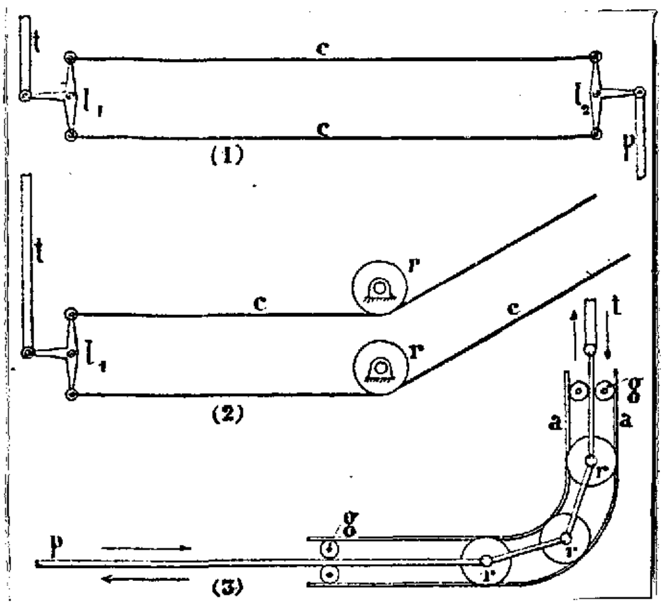


Fig. 105. Transmission by levers or rods.

the direct control of a centrifugal pump with vertical shaft placed at a given depth in a well located within the axis of the pylon, as may be seen in Fig. 117. /157

The centrifugal pump should be secured as close to water level as possible to facilitate suction and starting; it is equipped with a strainer and a foot-valve k.

The shaft of the pump p is driven by a gear train which multiplies the speed of the shaft t of the wind motor in a suitable ratio. This shaft t is guided and /158 supported by a given number of vertical bearings bb mounted on rods embedded in the walls of the well. An installation of this type should include a platform at the level of the pump and an iron ladder affixed to the wall of the well, to facilitate lubrication and maintenance of the pump, /159 the gears and the vertical bearings.

3. Electrical Transmission

A generator is installed at the top of the pylon. This generator driven by gear trains multiplying the rotation speed of the wind wheel, keyed directly into the main shaft of this wheel.

The generator is generally a compound or anti-compound dc generator. As it follows the swiveling motions of the wheel in the wind, it transmits the current to cables attached to the pylon by two brushes acting on bronze rings. The entire assembly is housed in a watertight gearbox which protects it from the weather and provides lubrication for six months to a year.

Fig. 118 shows the Aurora windmill (Denmark) with its generator and the inside of the gearbox housing the multiplying gears; a is the shaft of the wind wheel and d the shaft of the generator. /160

The Adler Wind generators (Germany) also use a generator placed at the top of the pylon, with direct transmission through cut gears, in an oil bath, which require lubrication only twice a

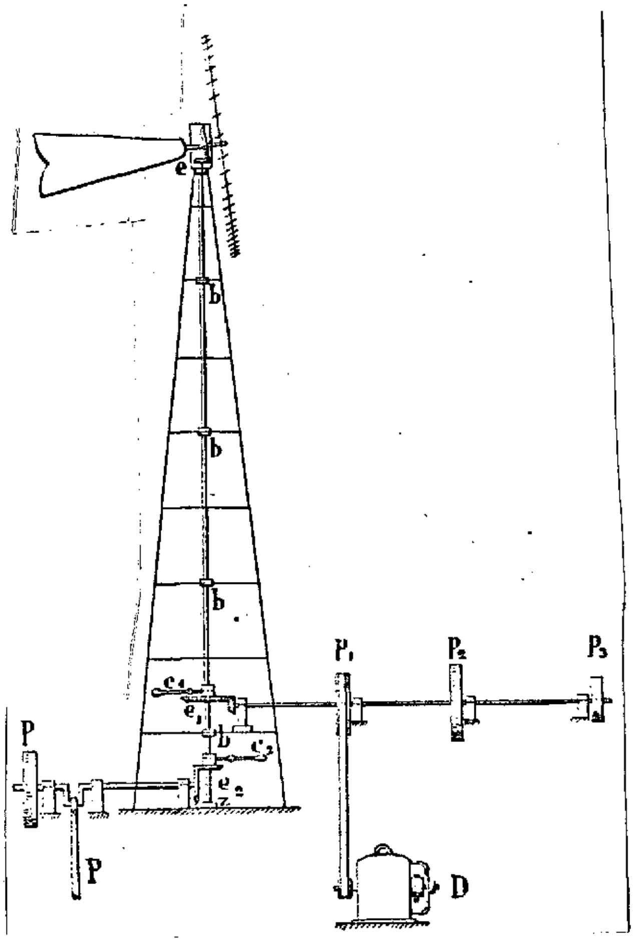


Fig. 106. Vertical shaft transmission.

year.

The generator is the "anti-compound" type with a stabilizing winding ensuring appreciably constant voltage despite variations in the wind speed. The voltage is 32, 55 or 110 volts, depending on needs.

The electrical current generated by these assemblies is used directly to drive electric motors or to charge a storage battery which serves as a voltage regulator.

This will be discussed further in the chapter on production of electricity by wind motors, which will also describe the circuit breakers and current regulating devices.

The efficiency of electro-dynamic transmission systems is not as high as that of a simple mechanical transmission using rods or gears, but it is the only attractive method for transmitting energy over large distances or powering lighting systems. Here the efficiency of a generator installed at the top of a pylon is higher than that of a generator driven by a vertical shaft and a bell-crank lever on the ground.

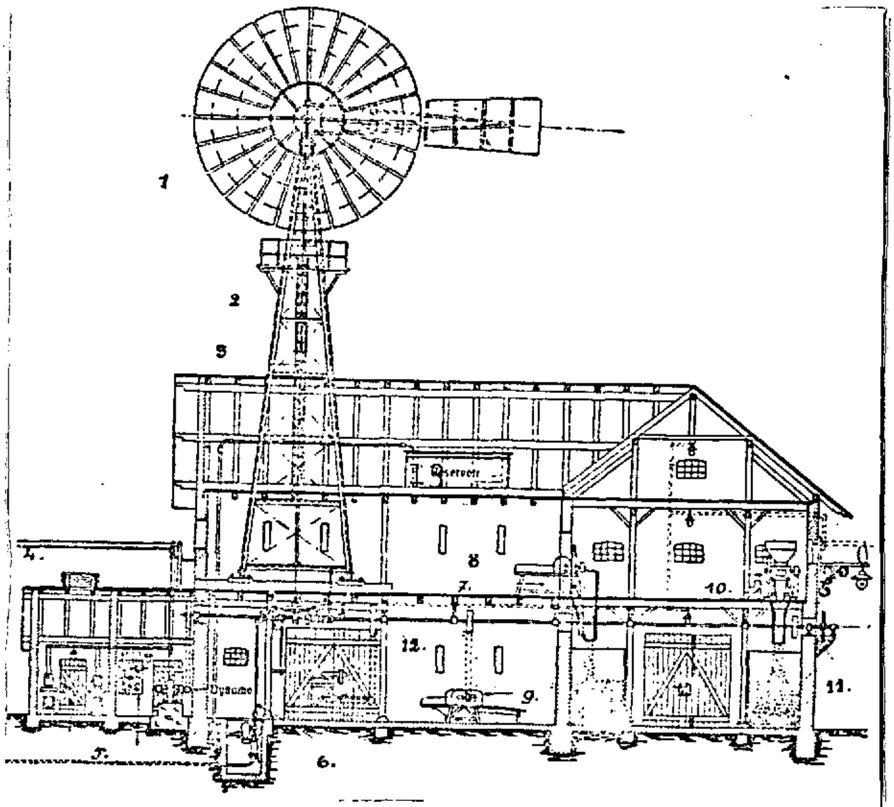


Fig. 107. Diagram of the installation of a wind motor atop a building to power various agricultural, lighting and water pumping equipment. The transmission from the wind wheel to the main shaft of the building consists of a vertical shaft.

Key. 1. Wind motor with rotary transmission; 2. Steel pylon; 3. Vertical rotating shaft; 4. Outside electrical circuit; 5. Switch panel; 6. Transmission to pump; 7. Bevel gears; 8. Chopping or crushing machine; 9. Thresher; 10. Pounding or flattening mill; 11. Wheel for transmission by cable; 12. Transmission shaft; 13. Tank.

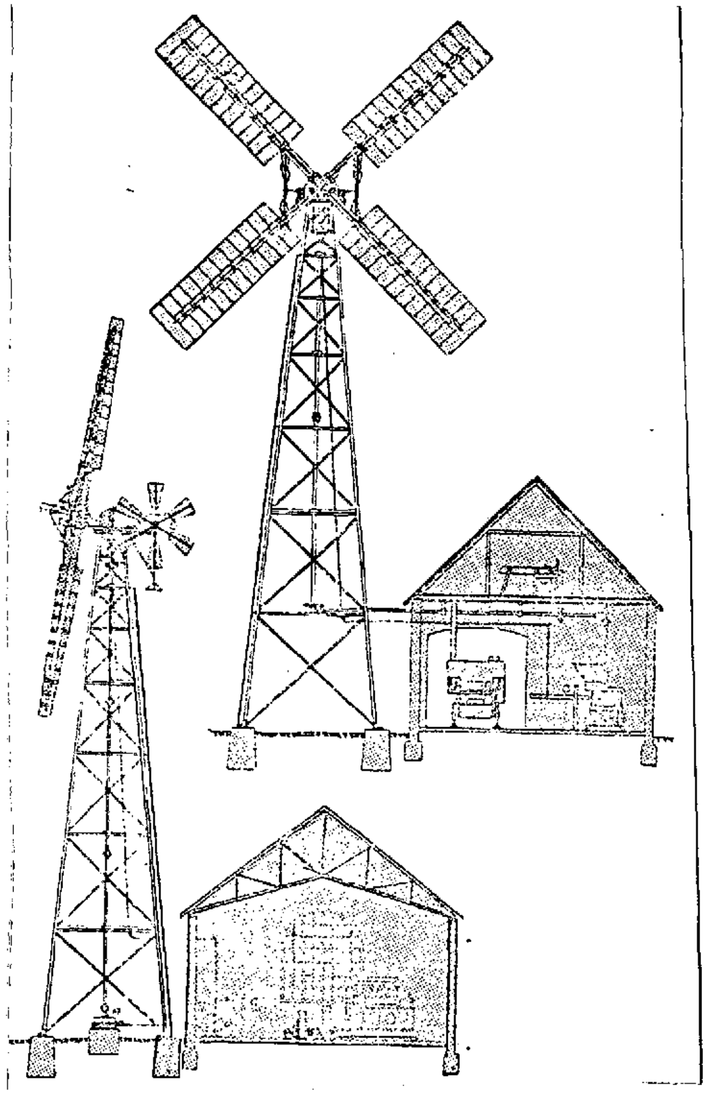


Fig. 108. Two Danish windmill installations

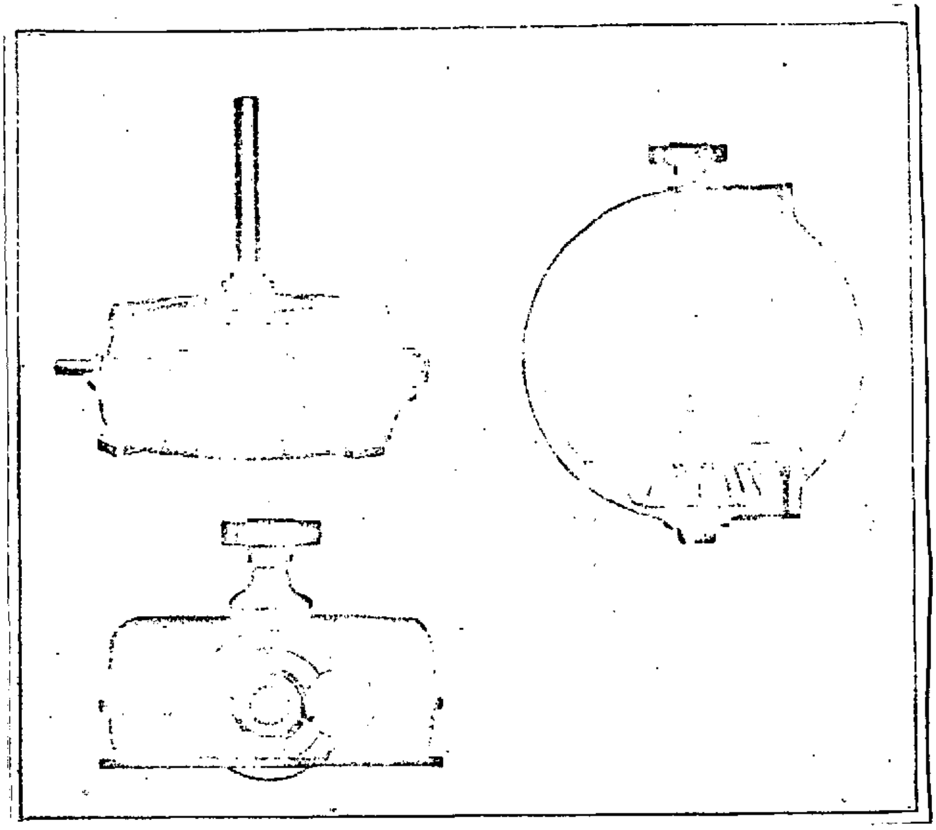


Fig. 109. Bevel gearbox at the foot of a pylon with a high multiplying gear ratio.

Fig. 110. Perspective view of gearbox shown in Fig. 109, open.

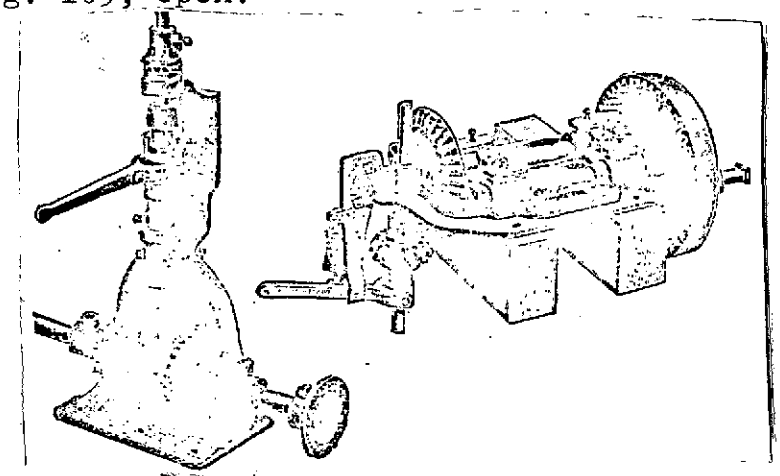


Fig. 111. Gearing for base of pylon (Durey-Sohey).

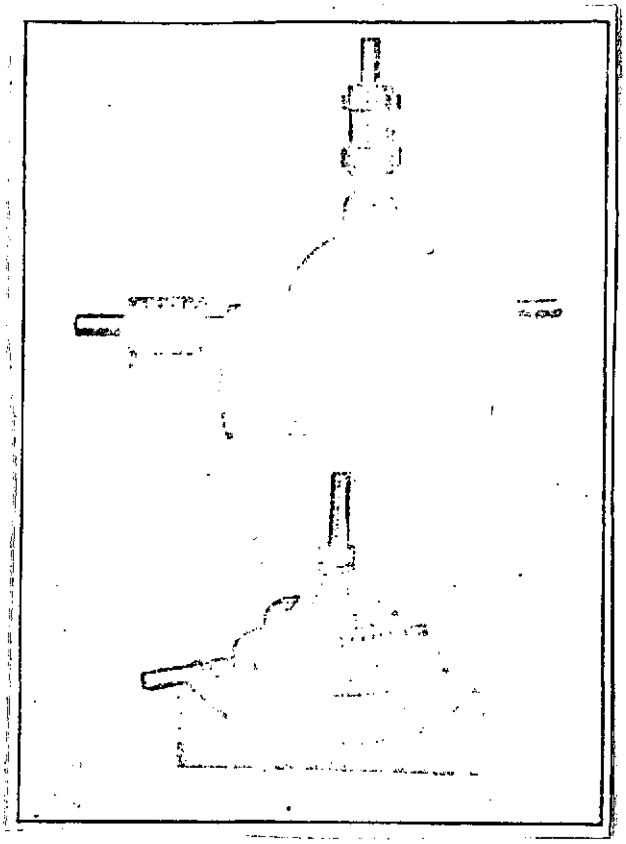


Fig. 112. The gearbox designed by Friedrich Köster, in open and closed positions. The toothing ratio is from 1:4 to 1:1 for ordinary transmission systems and from 9:1 to 2:1 for the direct driving of pumps.

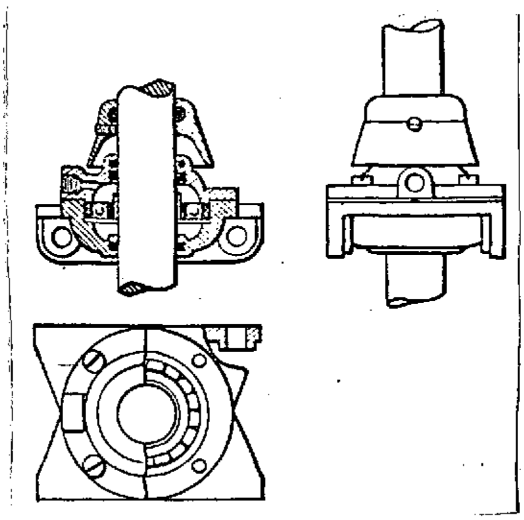


Fig. 113. Structural details of the Cyclone vertical ball bearing.

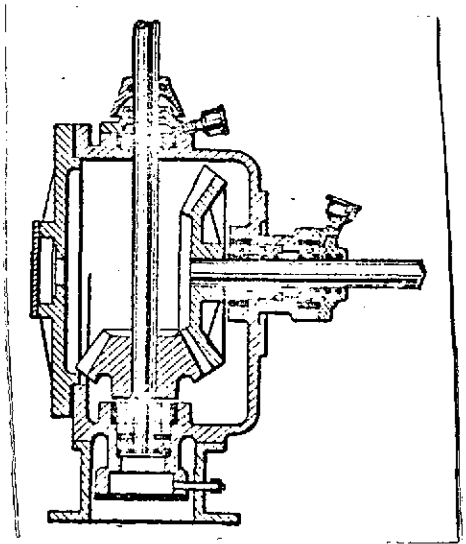


Fig. 114. Structural details of the gearbox at the base of the pylon.

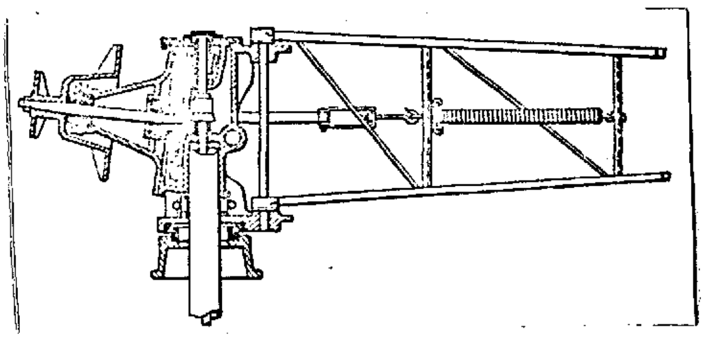
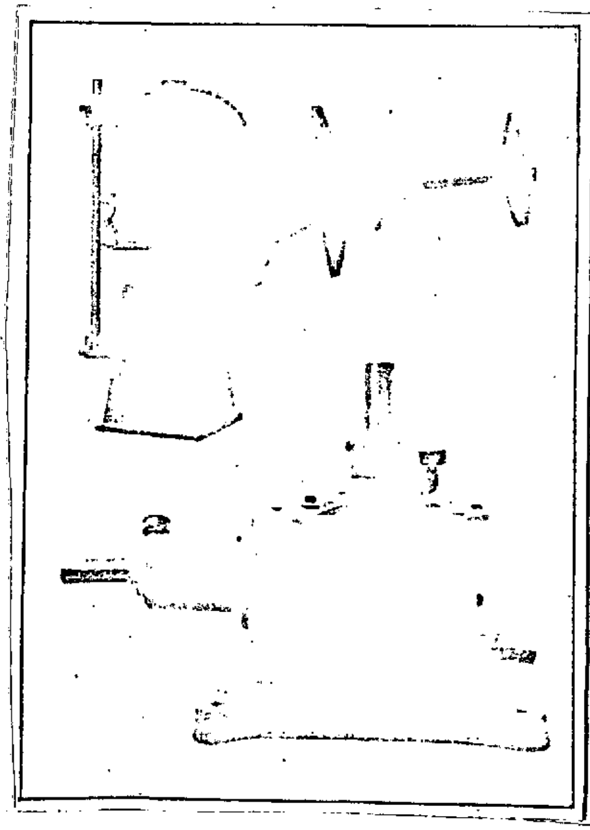


Fig. 115. Head of the Cyclone wind generator.



Figs. 115 a and 116. Cyclone gearboxes

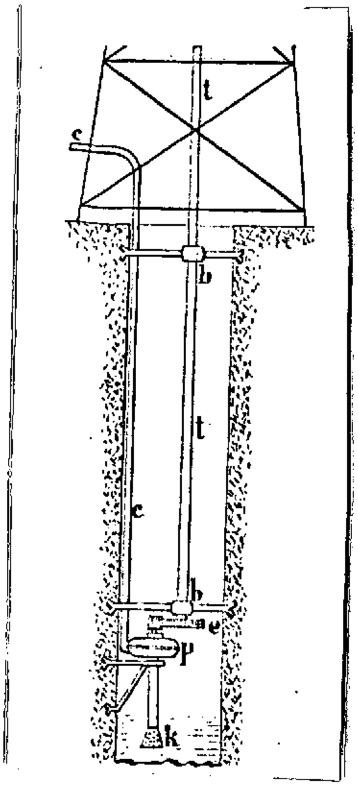


Fig. 117.
Driving
a centrifu-
gal pump.

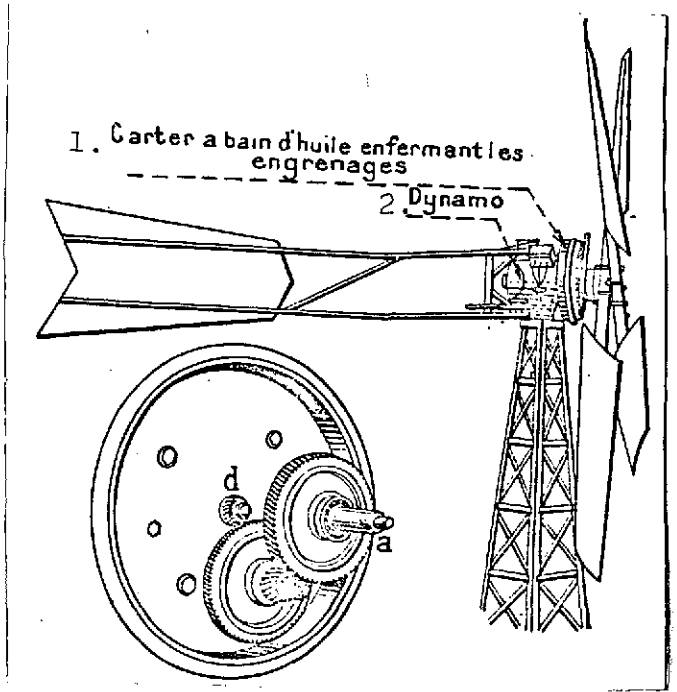


Fig. 118. The Aurora wind motor with generator mounted on the pylon.

Key. 1. Gearbox with oil bath.
2. Generator.

Fig. 119. Multiplying gears (inside gearbox with oil bath).

Pressure of the Wind on Wind Motors. Stress on Pylons.

Diagram 1 in Fig. 120 gives a basic representation of a paddlewheel R mounted on a pylon. The stress of the wind on the wheel is indicated by the force p_r applied at the center of the wheel and the stress of the wind on the pylon is given by the force p_p applied at the center of gravity of the surface open to the wind.

This surface is an isosceles triangle whose center of gravity is one-third of the height from the base at c. To determine the result of forces p_r and p_p, force p_r is extended for a length om equal to p_p and p_p is extended by a length cn equal to p_r. The point u where the straight line mn intersects the axis of the front of the pylon is the point of application of the resulting force p_t, whose value is the sum of the forces p_r and p_p.

The point u', which is the pressure center of the wind on the assembly, may be determined graphically as given in Diagram 1, but it also may be computed by writing:

$$uo + uc = oc = \frac{2h}{3},$$

h being the height from the ground to the shaft of the wheel R, and

$$uo \times p_r = uc \times p_p.$$

Solving these two equations, one obtains:

$$uo = \frac{2h \times p_p}{3(p_r + p_p)} \qquad (1)$$

To determine the values of p_r and p_p, the computations must be based on the highest wind pressures occurring i.e. 300 kg/m^2. This is the wind pressure occurring in the most violent hurricanes. /162

The area which the wheel offers to the wind when it is facing into the wind may be estimated at only half of the geometrical area of its circle. Of course, the wheel should turn aside during storm winds, but it may be prevented from doing so by a malfunction of the mechanism, and in this case its entire area would be exposed to the hurricane, an accident which should be prevented. We will therefore estimate the entire resisting area of the wheel at $\frac{\pi R^2}{2}$. The pylon, which is pyramidal with triangular faces, will be subjected to stress from the wind not only on the angle-irons facing the wind but also those at the rear.

Without computing the exact area which these four sides of the pylon present to the wind in this way, one can make a fairly close estimate of this area as one-third of the area of one side for a pylon consisting of steel angle iron, and half of the area of one side if the pylon is made of wood. If the pylon has a water tank or if its walls are more or less filled in by solid walls, these surfaces opposed to the wind must be added to the above estimated area of the posts and cross-beams.

For example, let us assume a pylon consisting of steel angle irons with a height of 20 m to the shaft of the wheel and a square base 4 m on a side, with a wheel 6 m in diameter at its top.

The total area of the wheel will be 28.27 m^2 and its area resistant to the wind will be 14.14 m^2.

The total area of one face of the pylon will be $\frac{20 \times 4}{2} = 40\ m^2$, and its area resistant to the wind will be 13.33 m^2.

The maximum pressure of the wind p_t will therefore be:

$$(14.14 + 13.33)300 = 8{,}241 \text{ kg}$$

applied at point u, determined as described above.

To compute the stress transmitted to the anchoring points a and b, one need only break down the force p_t into two other forces, one acting by tension on the face ao exposed to the wind, and the other by compression at point b, along the direction ub. These two forces are given by the parallelogram utvk, and their algebraic expressions are:

$$\text{ut (tension at a)} = \frac{p_t \sin \beta}{\sin \alpha} \qquad (2)$$

$$\text{uk (pressure along ub)} = \frac{p_t \sin \gamma}{\sin \alpha} \qquad (3)$$

To facilitate the measurements these quantities may be measured on the diagram, if the latter is exact. /163

Finally, the pressure at b along the line ub may be broken down into two forces as shown by Diagram 2: one, bz, which compresses the ascending angle pieces along their axes, and another, by, which tends to slide the pylon along the ground.

If one wishes to determine the separate stresses produced by the wind on the pylon and on the wheel, it is sufficient to construct the force parallelograms for the pressures p_p and p_r as we have shown in Diagram 1 of Fig. 120. The wind pressure p_r on the wheel exerts the tension t_r and the compression k_r, and, on the pylon alone, the tension t_p and the compression k_v.

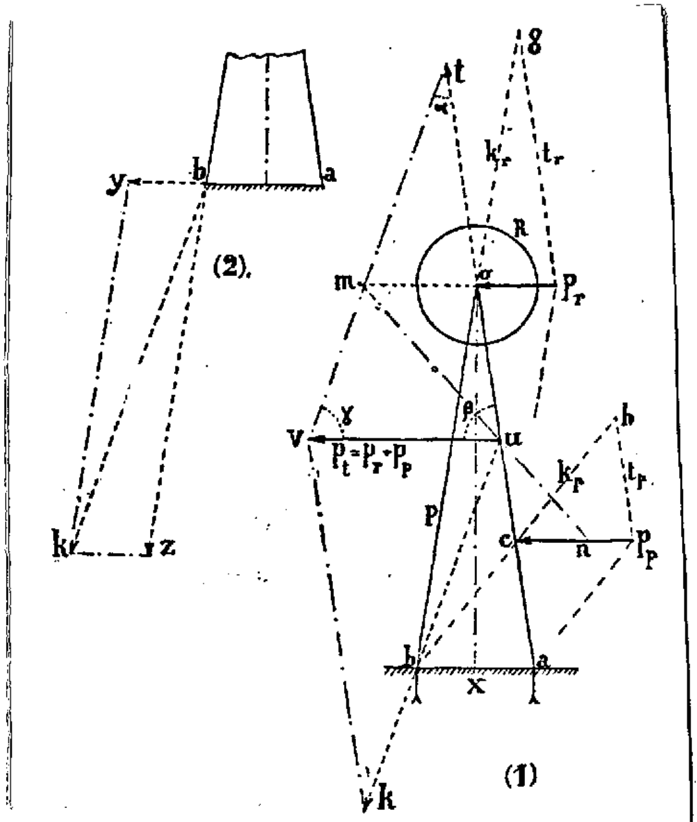


Fig. 120 - 121.

Simplified Method

Assuming that the average stress of the wind occurs along a vertical plane passing through the axis of the pylon, as shown in Fig. 122, the stress of the wind may be shifted to the peak o of the pylon p_p, provided that its moment in relation to the embedding point x does not change. /164

The point of application of the force pp being at the center of gravity of the vertical triangle, that is, at one-third of the height from point x, the sum of the pressure p_r on the wheel and that on the pylon applied at the peak o will be:

$$p_r + \frac{p_p}{3} = p$$

and the tension and compression stresses, equal on both faces of the pylon, will each have the value:

$$t = k = \frac{p}{2 \cos \beta}$$

β being the angle the base of the pylon makes with the horizon. In pylons with a square base, the stresses are distributed on two of the legs; the stress of the wind on a single leg will therefore be:

$$t = k = \frac{4 \cos \beta}{p} = \frac{p_r + \frac{p_p}{3}}{4 \cos \beta}$$

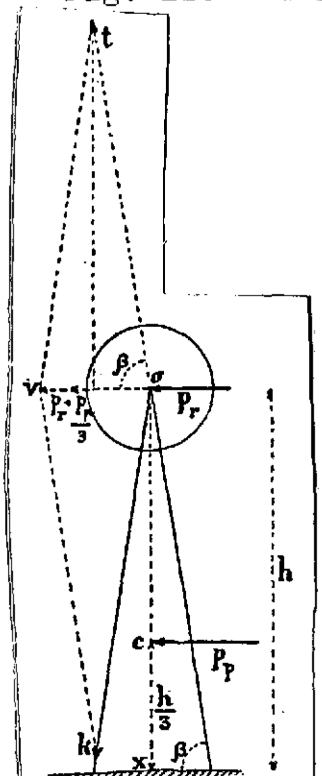


Fig. 122.

If the height of the pylon is three times a side of its base, $\cos \beta = 0.156$ ($\beta = 81°$); for $h = 4b$, $\cos \beta = 0.122$ ($\beta = 83°$). Finally, for $h = 5b$, as in Diagrams 2 and 3 of Fig. 134, $\cos \beta = 0.087$ ($\beta = 85°$). To divide the value $p_r + \frac{p_p}{3}$ by $\cos \beta$ thus amounts to multiplying this value by 3, 4 or 6 in the three cases considered above, which gives some idea of the significance of these stresses on the legs of the pylon.

Compression Due to the Weight of the Assembly

The weight of the wind motor and that of the pylon produce a compression stress on the uprights of the pylon which must be added to that arriving from the pressure of the wind.

Thus the weight of this wheel and pylon assembly must be estimated as closely as possible and divided by the number of legs on the pylon; let f equal this stress on one leg. During the thrust of the wind, the legs undergoing tension will be subjected to the tension due to the wind minus this quantity f. However, the uprights subjected to compression will undergo the sum of the compression stresses due to the wind and the weight f, and as a result, their fatigue will be greater than those subjected to tension. /165

This explains why, when a pylon is overturned by the wind, it is always the uprights on the side away from the wind which are bent, while those subjected to tension are never broken.

Numerical Application to a Steel Pylon With Four Uprights

As an example, let us take the figures given at the beginning of this chapter, assuming an angle $\beta = 85°$ ($p = 5b$), a pylon height of 20 m, and a distance between the bases of the legs of 4 m.

Total area of wheel: 28.27 m^2.

Area resistant to wind: 14.14 m^2.

Pr, maximum pressure of wind on the wheel not turned aside.

14.14 x 300 = 4,242 kg.

Total area of one face of the pylon: 40 m

Area resistant to wind: 13.33 m^2.

P_p, maximum pressure of wind on the pylon: 13.33 x 300 = 3,999 kg.

$$P = p_r + \frac{p_p}{3} = 4,242 + \frac{3,999}{3} = 5,575 \text{ kg};$$

$$t = k = \frac{5,575}{4 \cos \beta} = \frac{5,575}{4 \times 0.087} = 16,020 \text{ kg}.$$

To this stress must be added one-fourth the weight of the pylon and the wheel, which we will assume to be estimated at 4,000 kg, that is, 1,000 kg for each leg of the pylon. As a result, the maximum stress on one of the legs of the pylon will be 17,000 kg.

Assuming the stress on the steel to be 13 kg/m^2 (the accepted stress for reinforced concrete), a cross section of one angle iron at the anchoring point of one of the legs should be $\frac{17,000}{13}$ = 1,310 mm^2, which corresponds to an angle iron measuring 90 x 90 x 8. (See table below.) /166

TABLE OF MILD STEEL ANGLE IRONS

Equal vanes			Unequal vanes		
Profiles in mm	Weight per m in kg	Cross sections in mm^2	Profiles in mm	Weight per m in kg	Cross sections in mm^2
40×40×4	2,570	304	50×30×5	2,920	375
45×45×4.5	3,200	384	60×40×5	3,700	475
50×50×5	3,700	475	70×50×5	4,480	575
55×55×5.5	4,500	575	80×40×7	6,180	791
60×60×6	5,335	684	80×50×7	6,720	861
65×65×6.5	6,260	803	80×60×7	7,260	931
70×70×7	7,300	931	90×70×8	8,480	1,216
80×80×8	9,500	1,216	100×60×10	11,700	1,496
90×90×9	12,000	1,539	100×80×8	10,700	1,359
100×100×10	15,000	1,900	110×70×8	10,700	1,376
110×110×11	17,750	2,299	120×80×9	13,400	1,719
120×120×12	21,350	2,736	130×90×11	17,900	2,299
150×150×14	31,250	4,004	150×80×12	21,300	2,736

Note. The corner-posts always consist of equal angle irons, but it is advantageous to construct the horizontal cross-beams and the braces, which are subject to transverse bending, of unequal angle irons, the broadest flange being placed in the vertical plane.

Pylons With Parallel Uprights

This arrangement is frequently used for pylons supporting a water tank, like those shown in Figs. 123, 125 and 127. In this case, the force of the wind should be computed as shown in Fig. 123: the pressure of the wind is applied at the center of gravity at the prism made up of the pylon, that is, at half of its height xh, at o.

By joining o to the ends of the vertical plane a and b and decomposing the force p_p according to its directions, one /167
obtains two equal forces of tension and compression t and k.

By connecting these forces to points a and b by lines t_1 and k_1, and by decomposing them, one obtains the forces acting vertically on the feet of the pylon, T and K, and for one face of the pylon one has

$$t = k = \frac{P}{2 \cos \beta}$$

$$\text{and } T = K = \frac{P \sin \beta}{2 \cos \beta} = \frac{P}{2} \tan \beta.$$

If the pylon has 4, 6 or 8 legs one divides by 4, 6 or 8.

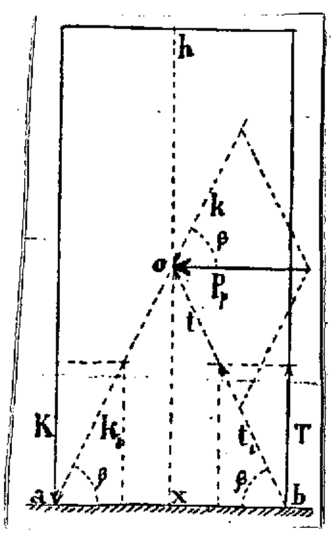


Fig. 123.

Effect of the Weight of the Pylon and the Wheel on Stability

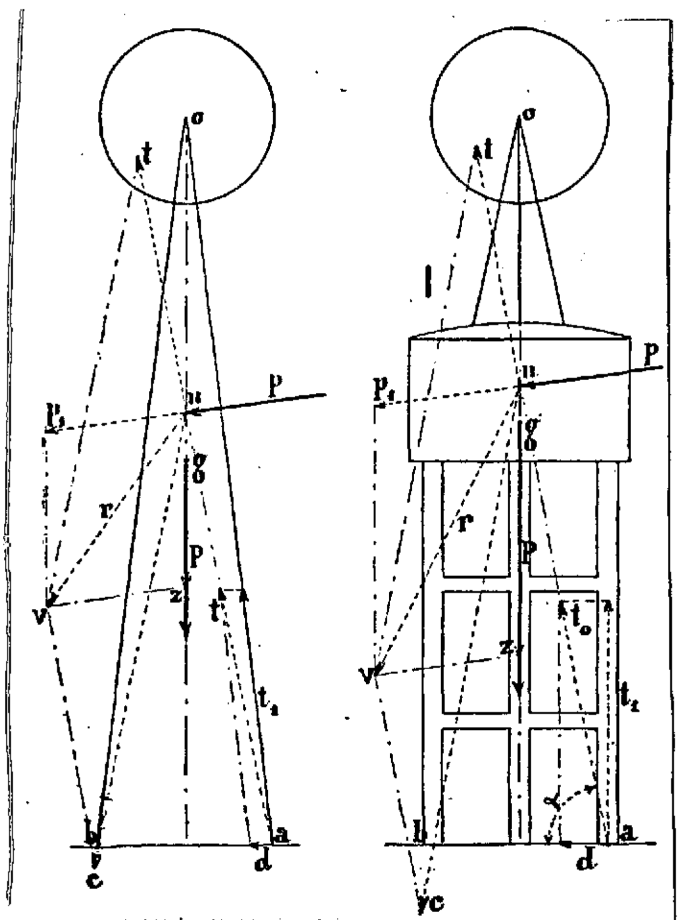
The stability due to the weight of the wind motor assembly is not very significant from the standpoint of resistance to the wind. If the pylon were simply placed on the ground and not anchored to deep, heavy foundations, it would be knocked down by a relatively low wind. In this respect, let us consider Figs. 124 and 125, in which the arrow P represents the weight of the assembly applied at the center of gravity G of the wheel and pylon assembly.[1] To overturn this assembly if it were merely placed on the ground, the center of gravity G must describe the arc of circle G_1 around the radius bg, which corresponds to a force fg which need be less strong as the pylon is

[1] To determine the center of gravity of the wheel-pylon assembly, this assembly is considered to be lying horizontally on the ground, and the parallel forces representing the weight of the pylon acting on its center of gravity and the weight of the wheel applied at the center of the disk are plotted. Thus the composition of these two parallel forces would be as we have shown in Diagram 1,

higher.

This "overturning" force is approximately one-fifth the weight P in a case where h = 3b, and it would be barely one-eighth the weight P with h = 5b.

In determining this force, one can neglect to take into /168
account the tension and compression stresses on the legs of the pylon, and consider these to be an additional safety factor. However, if one wishes to make use of these stresses, one can perform the composition of the weight P of the assembly with the pressure p of the wind, as shown in Figs. 124 and 125. The resultant r will be obtained, and its decomposition will yield the forces of tension ut and compression uc.



Figs. 124 and 125.

The force of tension ut extended to a on the base will yield the tension stress t_1, and the force of compression uc will be extended to the base at b and broken down as shown in Diagram 2 of Fig. 121 to yield the compression stress at b.

It may be noted that the compression stress here is significantly greater than the tension stress, which is understandable since the thrust of the wind forces a single side to bear the entire weight of the assembly.

Tank Mounted on Pylon /169

In this case, the above computations must be made with this tank assumed empty, which might be the case during a hurricane.

However, the weight

Fig. 120, and this will determine the position of the center of gravity of the wheel-pylon assembly. In a pyramidal pylon, the center of gravity is one-fourth the height from the base along the axis of the pylon.

of the water in a full tank must obviously be taken into account in determining the resistant cross sections of the legs of the pylon below the water tank.

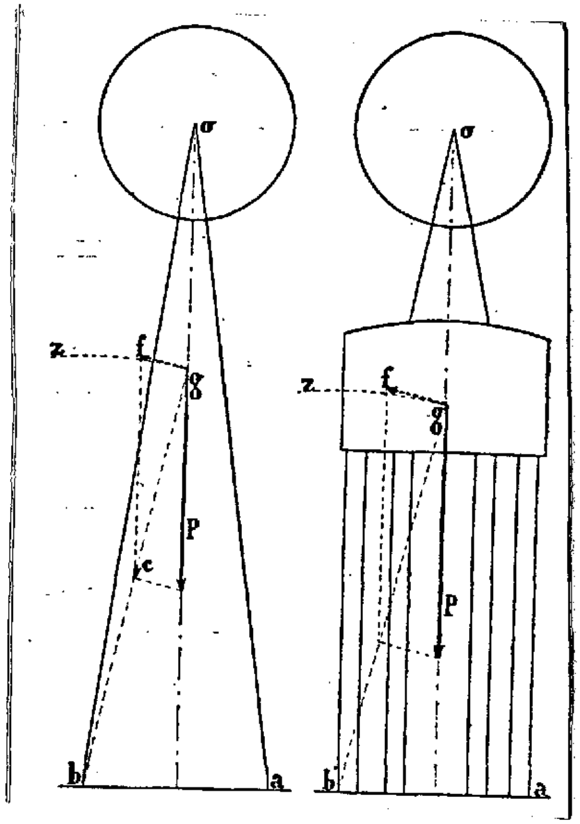
Distribution of Stresses on Legs of Pylon

In a pylon with a triangular base, the entire tension or compression stress may at times be exerted on a single leg. This happens with the tension when the wind is blowing on an angle of the pylon and with compression when the wind is blowing perpendicular to one of the faces. The three-upright configuration is highly disadvantageous, therefore, and is used virtually only for small assemblies of low height.

The four-upright pylon, with a square base, is generally used. The stresses are always distributed over two legs, or over a cross section equivalent to that of two /170
of these legs.

In a pylon with six legs and a hexagonal base the stresses must be considered as distributed over three legs.

In wooden pylons, the stress on oak or top-quality Swedish fir should not exceed 60 kg/cm^2 of the net mortise cross section, under tension or compression.



Figs. 126 and 127.

Construction and Assembly of Pylons

In the Congo, wind motors have been installed on high trees whose upper foliage has first been cut away. A sort of scaffolding is constructed of long branches or poles, and this serves as a ladder and upper platform around the large trunk of the tree.

A wind motor pylon may be constructed of fir trunks connected as cross-pieces and St. Andrew's crosses, firmly bolted into the four trunks forming the legs of the pylon. These pylons must always be given a pyramidal shape, making each of the sides of the square at the base between one-fourth and one-fifth the height of the pylon, measured from the top of the foundations to the shaft of the wind wheel.

When the weight of thewind motor is not too great and there is no rod or shaft descending vertically from the shaft of the wheel to the ground, as is the case when a generator is placed at the top of the pylon, the ladder may consist of a wooden post or a steel tube (of the pole or tubular post type) or a vertical lattice girder.

This post is then guyed at a given distance from its top to allow room for the movement of the blades, as shown in Fig. 128 (an installation constructed by the Electro-Mécanique Co.).

Wooden pylons may be constructed as a framework connected by tenons and mortises, but mortises have the disadvantage of considerably decreasing the resistance of the corner posts to tension. To avoid this drawback, the cross-pieces and the St. Andrew's crosses may be attached to the four corner posts by bolts on broad thick iron washers. If the wood subsequently dries out it is easy to retighten all the bolts, and the joints can be strengthened by nailing them with long steel spikes.

The cross-pieces and braces are constructed of 165 x 65 fir planks or with planks split in two lengthwise. /171

Fig. 130 shows a wooden pylon constructed in this way. In constructing wooden pylons, it should be kept in mind that rain-water will always be trapped in the joints, where it quickly rots the wood. Thus the insides of the mortises, the tenons and the flat or joggled joint surfaces must be coated with a thick paint composed of lead minium and linseed oil boiled with litharge.

All the wood in the pylon should be given two coats of carbonyl or boiling tar either before or after assembly.

If the legs of the pylon are merely buried in the ground, they will begin to rot very quickly, especially at the point at which they emerge from the ground. This rotting can be retarded by burning these posts superficially and coating them with tar while they are still extremely hot.

However, the installation costs for a wind motor /172
mounted on a pylon are too high to settle for precarious foundations of this type.

It is much better to build foundation dies of masonry stopped with cement mortar or reinforced concrete, in the same way as if the pylon were constructed of steel angle irons. Flat or U-shaped anchoring rods will be embedded in these foundations and bolted to the four wooden legs, which will merely rest on steel plates placed on the masonry.

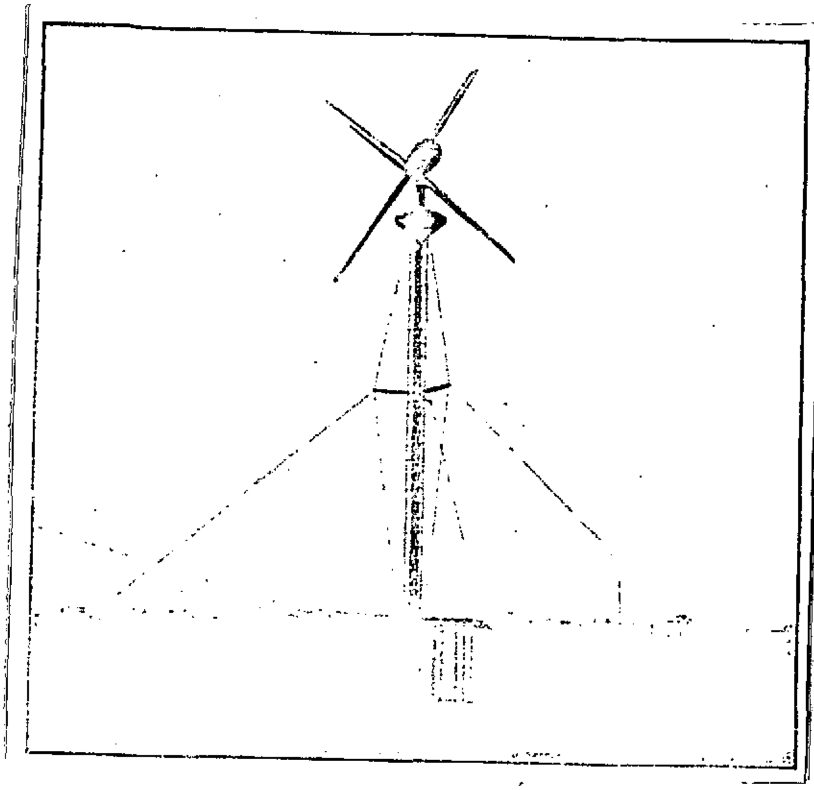


Fig. 128. Guyed post built by the Compagnie Electro-Mécanique.

In this way it is easy to re-coat the four legs of the pylon with tar at their base, which is most subject to rotting. Fig. 130 shows a wooden pylon resting on two cross-beams which in turn rest on the masonry foundation, in which the steel anchoring rods are embedded. /173

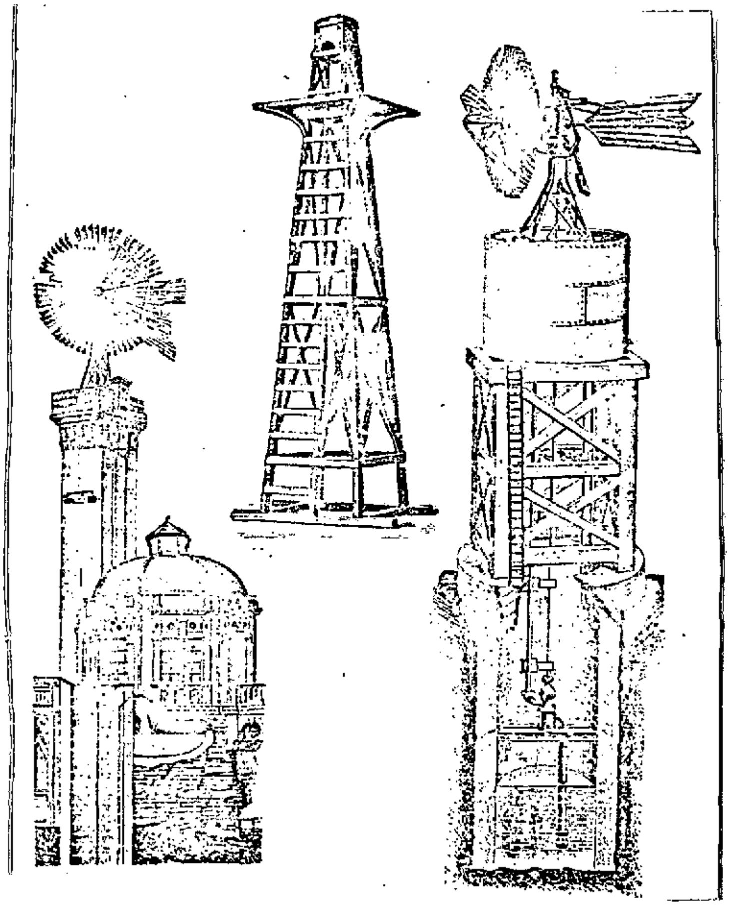
Steel pylons have three or four legs or uprights. Those shown in Fig. 132 and 133 are connected by horizontal cross-pieces and St. Andrew's crosses, the entire structure consisting of steel angle irons. The horizontal cross-beams are generally given a cross section equal to one-third the cross section of the corner uprights, and the rods forming the St. Andrew's crosses are given a cross section equal to one-half the cross section of the uprights.

All the rods are connected by hot riveting or by bolts on sheet metal gussets in accordance with ordinary ironworking practice. If the pylon is small, it may be assembled in the shop by hot riveting or even by autogenic welding, and is shipped to the site ready to be set up on the foundations. Large pylons, however, generally arrive at the site disassembled, and the joints are then bolted.

Some designers replace the angle iron St. Andrew's cross with stiffeners consisting of round steel rods or steel cables. /174
This will be discussed in a special section.

Diagrams 2 and 3 in Fig. 134 schematically show two methods of bracing steel pylons with square bases whose side is equal to one-fifth the height of the pylon.

The bases of the corner uprights rest on the top of the foundation, and the anchoring irons ee are riveted onto them as soon as the pylon has been set up.



Figs. 129, 130 and 131. Wood pylons and a masonry tower.

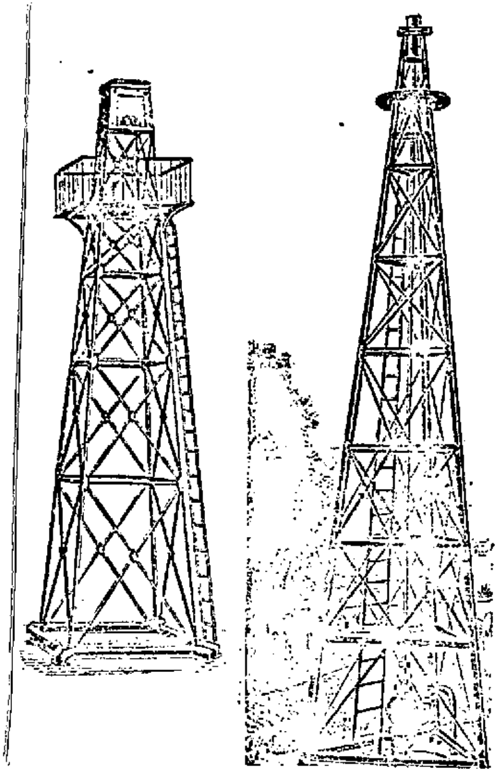
Diagrams 4 and 5 in Fig. 134 show two types of anchoring irons whose length includes the part embedded in the concrete foundation and the part aboveground. To work satisfactorily, the anchoring rods should reach to the bottom of the foundation and be bolted or riveted onto each of the corner uprights over a length equal to approximately one-eighth the height of the pylon. Thus the anchoring irons for a pylon 20 m high, for example, will each be 4-to 5 m long, and their cross section should be at least equal to that of the legs of the pylon.

In the foundation, these anchoring irons end in fishtails (Diagram 4), ends of angle irons riveted perpendicular to the strut (Diagram 5), or hooks anchored to the bottom bracing of the foundation die (Fig. 141). Some designers have the legs of the pylon end at the base in sole-plates (Fig. 131) or angle irons to which the round steel anchoring rods are secured by nuts. Fig. 140 (b) shows a U-shaped rod used as an anchoring strut by the Lykkegaard Company.

Steel pylons may be set up on masonry towers (Fig. 129), sheet metal tanks (Fig. 131) or reinforced concrete tanks (Figs. 135 and 142). In these cases their legs are firmly anchored on these supports.

A sheet metal or wooden tank can easily be housed inside a wooden or steel pylon.

The Aermotor Co. makes these tanks out of white pine, cypress or galvanized steel plates. They are mounted on wooden or angle-iron cross-pieces which in turn rest on the horizontal cross-pieces at a given level in the pylon and are covered with a



Figs. 132 and 133. Steel pylons.

conical lid.

The weight of these tanks contributes to the stability of the pylon.

Galvanized Steel Pylons With Stiffeners Consisting of Cables or Steel Rods

Rather than using angle irons as braces to distribute the stress on the pylon, some companies prefer the use of high-tension steel cables in an X configuration between the horizontal cross-pieces connecting the uprights. Figs. 137, 138 and 139 show /176
the structure of pylons constructed in this way by Goold Shapley and Muir Company of Brantford, Canada. The characteristics of these pylons are as follows:

Fig. 137. Height 20 m, double bracing, for areas exposed to extremely violent winds.

Fig. 138. Height 20 m, single bracing.

Fig. 139. Height 13.33 m, single bracing. /177

In all these pylons, the horizontal cross-pieces are approximately 1.50 m apart.

The Cyclone company of Compiègne, Oise, has used a system of tighteners consisting of round steel rods to brace its pylons.

Each of the steel cables or steel rods in these bracing systems must be equipped with a stiffening mechanism to correct their extension due to the effects of expansion and contraction by heat and cold, or their fatigue due to the stress of the wind.

This can be accomplished by connecting the steel cables to threaded rods or by threading the ends of the round steel rods. The tension is then adjusted merely by means of nuts tightened on angle irons, as shown by the three diagrams in Fig. 136 (Cyclone).

These construction procedures appear to be more complex and costly and appear to require more supervision than installing a bracing system consisting of angle irons riveted onto the uprights and cross-pieces of the pylon. However, they can be attractive nevertheless, in cases where disassembled pylons are shipped to areas where it is impossible to rivet the angle irons. /177 /178

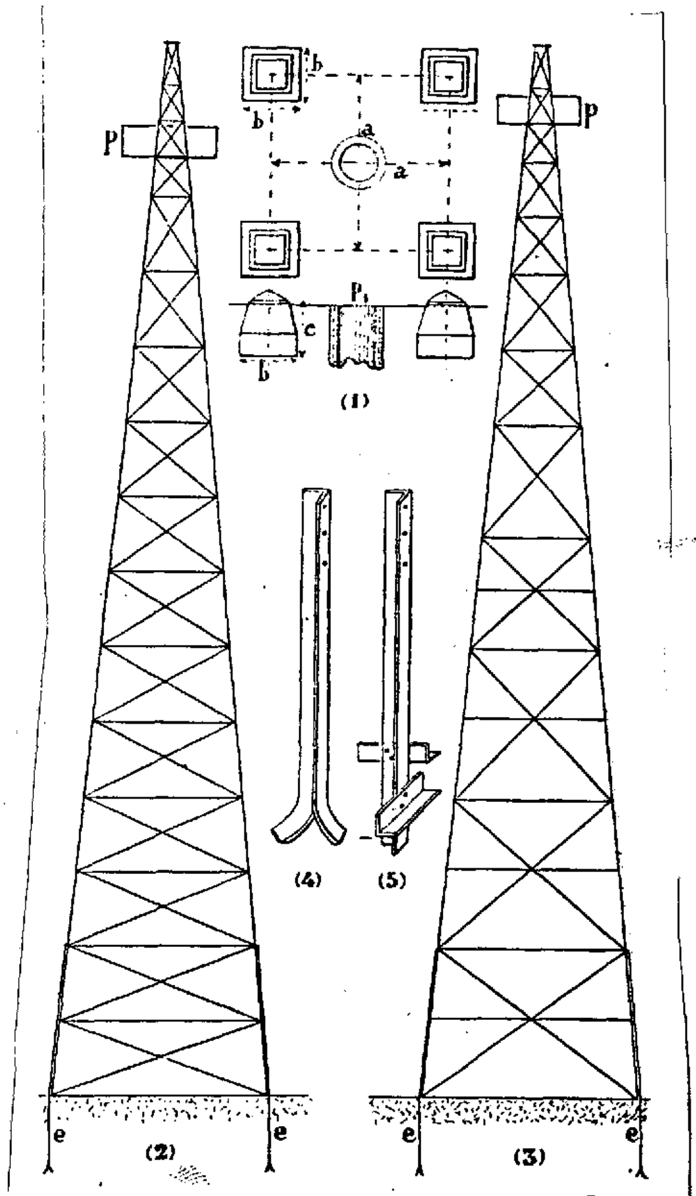


Fig. 134.

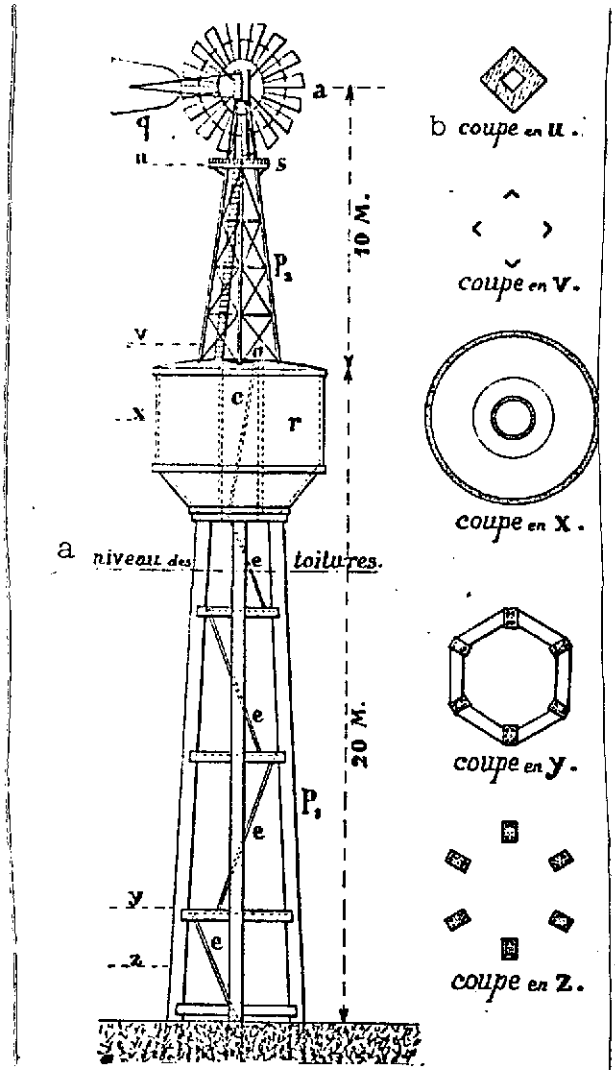


Fig. 135. Steel pylon mounted on a tank and a reinforced concrete pylon. (The wind motor of the Pas-de-Calais School of Agriculture. Wheel 4.20 m in diameter, tank capacity 150 m^3.)

Key. a. Level of roofing; b. Cross section at u (typ.)

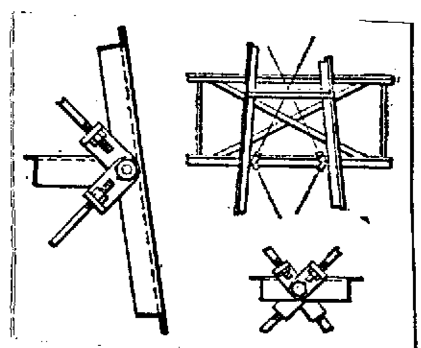
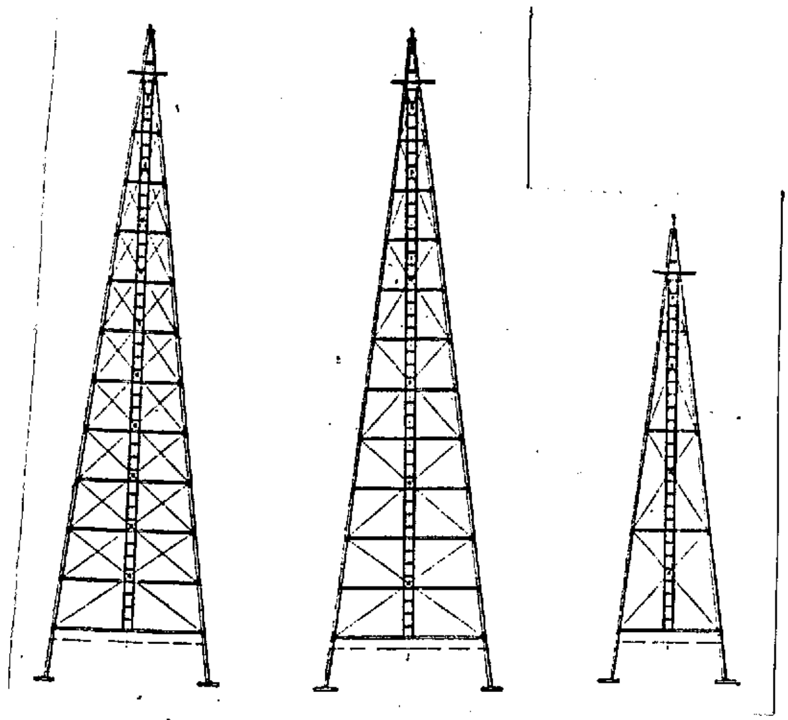


Fig. 136. Fasteners for steel stiffening components.



Figs. 137, 138 and 139. Pylons with stiffeners (Goold, Shapley and Muir).

DIMENSIONS AND WEIGHTS OF GALVANIZED STEEL PYLONS WITH STEEL CABLE STIFFENERS (FIGS. 137-139) FOR WIND MOTORS 2.50 TO 3 M IN DIAMETER /178

Height of pylon in meters	Weight in kilograms With 3 legs	/With 4 legs	Spacing of legs on the ground
6	140	164	1.60 m
9	190	240	2.25 m
12	277	368	3 m
15	368	470	3.75 m
20	470	624	5 m

The dimensions and weight of these pylons are roughly those used by Goold, Shapley and Muir of Brantford, Canada.

WEIGHT OF STEEL PYLONS FOR THE MAMMOUTH WIND MOTORS
(IN KILOGRAMS) (FIGS. 47 AND 48)

Diameter of wheel in m:	10	12	14	16	18
Weight of pylons:					
15 m high	1,500	1,950	2,400	2,475	2,925
20 m high	2,000	2,600	3,200	3,300	3,900

These pylons have four legs whose distance from each other on the ground is equal to the height of the pylon divided by 4.5.

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WEIGHT OF STEEL PYLONS FOR THE "STAR" WINDMILLS
MANUFACTURED BY FLINT AND WALLING MFG. CO.,
KENDALLVILLE, U.S.A.

Diameter of wheel in m	1.80	2.45 and 3	3.65	4.25	4.85
Height of pylon:	Weight of pylon in kg:				
6 m	178	183	222	348	405
9.10 m	246	260	325	490	575
12.20 m	336	364	455	655	765
15.20 m	435	493	605	845	980
18.25 m		662	800	1070	1215

These pylons have four pillars with angle-iron cross-pieces and round steel stiffeners serving as the bracing system. A side of the base is equal to the height of the pylon divided by five.

DIMENSIONS AND THICKNESSES OF STEEL PLATE USED IN RIVETED SHEET IRON TANKS WITH A CAPACITY OF 100 to 100,000 ℓ

Capacity in liters	Rectangular shape						Cylindrical shape				
	Dimensions			Thickness of plate			Dimensions		Thickness of plate		
	Length	Width	Height	Sides	Top and bottom	Approximate weight	Diameter	Height	Sides	Top and bottom	Approximate weight
				mm	mm	kg.			mm	mm	kg.
100	0.60	0.35	0.50	3	3	50	0.50	0.50	3	3	50
150	0.75	0.40	0.50	3	3	65	0.50	0.75	3	3	55
200	0.80	0.50	0.50	3	3	75	0.50	1.00	3	3	60
250	0.80	0.50	0.65	3	3	85	0.57	1.00	3	3	80
500	1.00	0.50	1.00	3	3	135	0.80	1.00	3	3	105
750	1.50	0.50	1.00	3	3	160	0.98	1.00	3	3	135
1,000	1.50	0.70	1.00	3	3	200	1.15	1.00	3	3	155
1,500	1.60	0.75	1.20	3	4	250	1.20	1.30	3	4	215
2,000	1.80	0.90	1.30	3	4	370	1.30	1.30	3	4	260
2,500	2.00	1.00	1.30	3	4	400	1.50	1.50	3	4	315
3,000	2.20	1.10	1.30	3	4	455	1.60	1.50	3	4	345
3,500	2.20	1.20	1.30	4	4	565	1.75	1.50	3	4	390
4,000	2.40	1.20	1.30	4	4	635	1.85	1.50	4	4	480
5,000	2.50	1.35	1.50	4	4	700	1.80	2.00	4	4	550
6,000	2.85	1.50	1.50	4	5	820	1.95	2.00	4	4	610
7,000	2.75	1.70	1.50	4	5	975	2.20	2.00	4	4	695
8,000	2.75	1.50	2.00	5	5	1,200	2.00	2.60	4	4	750
9,000	3.00	1.50	2.00	5	5	1,285	2.15	2.60	4	4	815
10,000	3.00	1.70	2.00	5	5	1,390	2.25	2.60	4	4	865
12,000	3.00	1.60	2.60	5	5	1,660	2.45	2.60	4	4	845
15,000	3.00	1.95	2.60	5	5	1,850	2.50	3.00	4	4	1,075
20,000	3.40	2.00	3.00	5	5	2,400	2.90	3.00	4	5	1,375
25,000	4.00	2.10	3.00	5	5	2,825	3.30	3.00	5	5	1,890
30,000	4.50	2.25	3.00	5	6	3,300	3.55	3.00	5	5	2,070
35,000	4.75	2.50	3.00	5	6	3,900	3.90	3.00	5	5	2,315
40,000	4.00	2.50	4.00	5	6	4,250	3.60	4.00	5	5	2,650
50,000	4.60	2.80	4.00	6	6	5,500	4.00	4.00	5	6	3,060
60,000	4.35	2.80	5.00	6	7	6,700	4.40	4.00	6	6	3,900
70,000	4.70	3.00	5.00	6	7	8,000	4.45	4.50	6	6	4,500
80,000	5.10	3.15	5.00	6	7	9,500	4.50	5.00	6	6	4,900
100,000	6.00	3.40	5.00	7	7	11,200	5.10	5.00	6	7	5,950

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Foundation Dies of Steel Angle-Iron Pylons /181

These foundation blocks or dies constructed under each of the uprights of the pylons are adequate when the ground is hard, that is, consisting of compact earth which is not swampy or saturated, or rocks to which the concrete is able to adhere firmly. For these cases, the following are the dimensions recommended by constructors for these foundation dies, as given in Diagram 1, Fig. 134.

According to the Aéromoteurs Cyclone Company of Compiègne:

SPACING BETWEEN LEGS OF PYLON A (IN METERS)

Height of pylon	8	10	12	14	16	18	20	21	24	28
Spacing of legs	1.80	2.20	2.50	3.00	3.40	3.80	4.20	4.60	5.00	5.40

DIMENSIONS b AND c OF FOUNDATION DIES, DEPENDING ON THE DIAMETER OF THE WIND WHEEL AND THE ABOVE SPACING

Diameter of wheel	2.80 to 3.00	3.00 to 3.50	4.20 to 4.80	5.70 to 6.50	7.50 to 8.50	9.00	10.00	11.00	12.00
Dimensions of: b	0.80	0.90	1.00	1.10	1.20, 1.25	1.30	1.30	1.50	1.60
c	1.00	1.10	1.20	1.40	1.60, 1.65	1.70	2.00	2.20	2.50

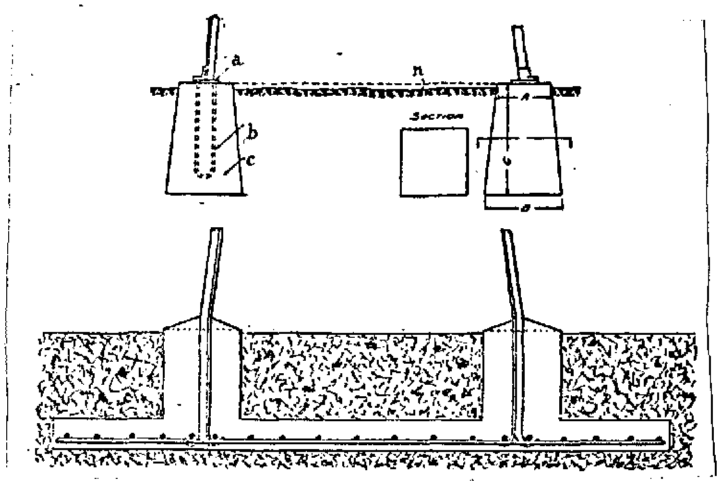
According to the Lykkegaard Company:

FOR ITS "MAMMOUTH" WIND MOTORS AND PYLONS 20 M HIGH, AS GIVEN IN FIG. 140

Diameter of wheel		7	9	10	12	14	16	18
Dimensions of dies	A	0.7	0.7	0.8	0.8	0.9	0.9	1.0
	B	0.9	0.9	1.0	1.0	1.1	1.1	1.2
	C	1.3	1.3	1.4	1.4	1.6	1.7	1.8

We recommend making the upper, aboveground part of the foundation dies pyramidal in shape, which will prevent the stagnation of rainwater around the bases of the pylon. /182

If the ground is soft or swampy the foundation dies will not be adequate, and it will be necessary to construct a foundation apron of reinforced concrete or firm masonry stopped with hydraulic lime mortar or cement and reinforced with a number of iron bars approximately 15 mm in diameter, intersecting in the rock mass and anchored to the legs of the pylon. It will always be advantageous to make the area of this apron greater than that occupied by the base of the pylon; the length and width of the apron can easily be obtained by multiplying the spacing between the feet of the pylon by 1.5, 1.75 or 2, depending on the condition of the terrain.



Figs. 140 and 141. Anchoring struts and foundations.

The depth of the apron in the ground will be the same as that given above for the foundation dies, and its thickness between the dies will be one-fourth of their height.

The foundation will appear in cross section as shown in Fig. 141. It will be noted that the weight of the earth piled on top of the apron will help keep the pylon from overturning.

Fig. 143 shows a foundation system designed by Friedrich Köster of Heide in Holstein, which includes bolts sunk to a considerable depth with convex distribution plates in concrete aprons. The legs of the pylon are equipped with strong sockets into which these bolts are screwed.

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Foundations in Sand

In order to install wind motor pylons in sandy desert areas, the Cyclone Company has patented a foundation system consisting of a large cubicle steel sheet box at each foot of the pylon, filled with sand and hermetically sealed to prevent the sand from being blown out by the wind. Each foot of the pylon is anchored at the bottom of this box by a large cast plate reinforced with ribbing.

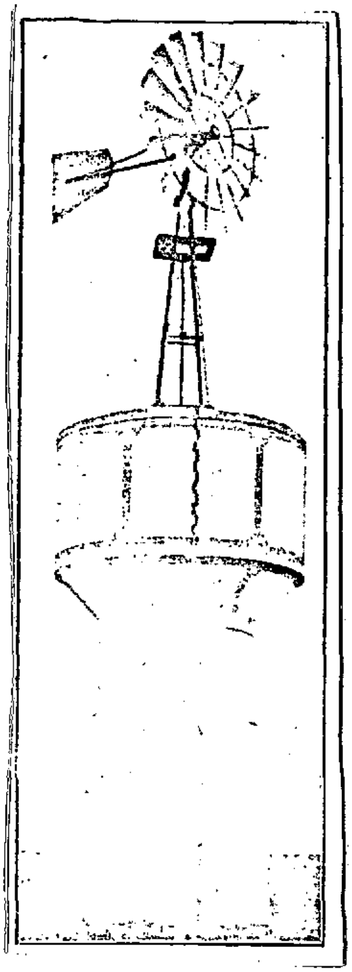

Fig. 142. Water supply for the community of Monchauvet (S.-and-O.), population 256; 20 m³ per day, elevated to a height of 55 m.

In this system, the sheer weight of the four boxes of sand ensures the stability of the pylon, even if the wind should blow away the sand which covers them on the outside during normal weather.

Setting Up Of Pylons

To mount a small-diameter wind motor on its pylon, the latter is almost always assembled previously and laid horizontally on the ground. Thus the pylon and the motor are raised at the same time, ready for operation.

If a derrick is available, the hoisting operation can be performed as shown in Fig. 144.

The derrick is set up so that its feet cc are at a distance from the base of the pylon equal to one side of the base, with the result that when the pylon is set upright, its base will come into contact with the derrick and thus will be positioned on the foundation dies d. The derrick is propped from the rear by a rigid strut q and guyed by wires hh. /184

The legs of the pylon rest on two of the foundation dies and are stopped by a beam S kept in place by two stakes firmly embedded in the ground z.

Two cables kk attached to the top of the pylon are moored on each side to stakes pp implanted at a distance from the base s equal to approximately two-thirds the height of the pylon and along a line xy which is an extension of the base s. The purpose of these two cables is to prevent the pylon from turning over to one side.

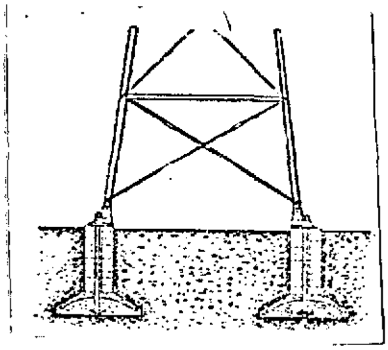

Fig. 143. Foundation anchoring system.

A restraining cable u attached to the top of the pylon serves to moderate the rate of fall onto the foundation dies.

The hoisting cable l should be attached to the pylon at a height roughly equal to that of the derrick. This cable passes through a pulley r and is drawn by the winch t.

If no derrick is available, the hoisting procedure may be performed as shown in Fig. 145. Two of the legs of the pylon are placed on two of the foundation dies and stopped by a sill s. One then attaches the lateral balancing cables kk and a restraining cable r, for which a stake u is emplanted, the

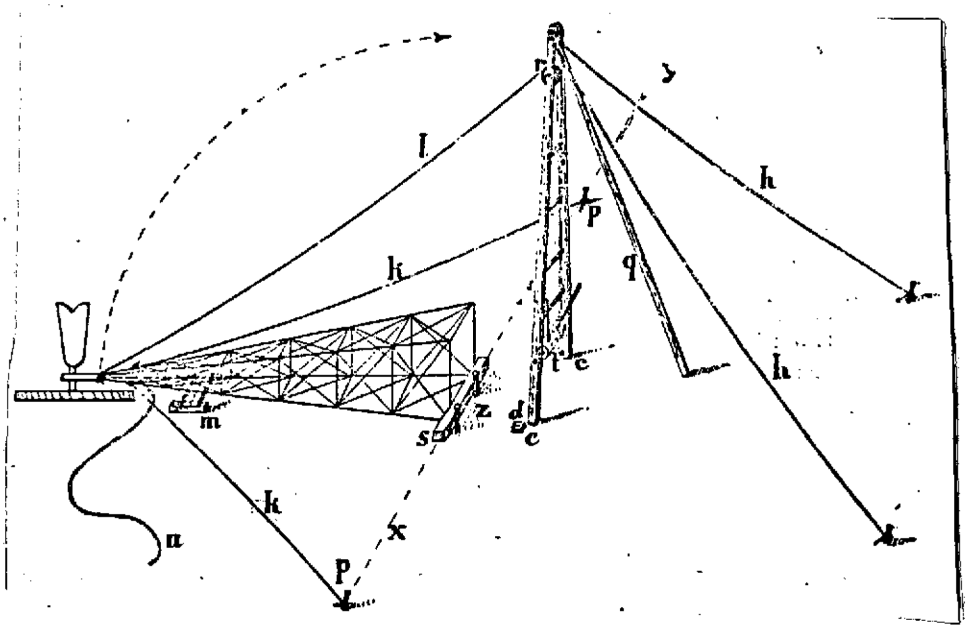

Fig. 144. Hoisting by derrick

entire setup being the same as that described above.

The hoisting cable l passes between two putlogs or poles /185
whose height is equal to at least half the height of the pylons, or more, if possible. These two putlogs are connected at b, toward their tops and toward their spread feet, so as to give them high lateral stability. This hoisting cable is drawn by a pulley block, or better yet, by a winch t firmly moored to stakes a embedded in the ground. The most suitable type of winch for this task is a chain winch with sheaves and gears.

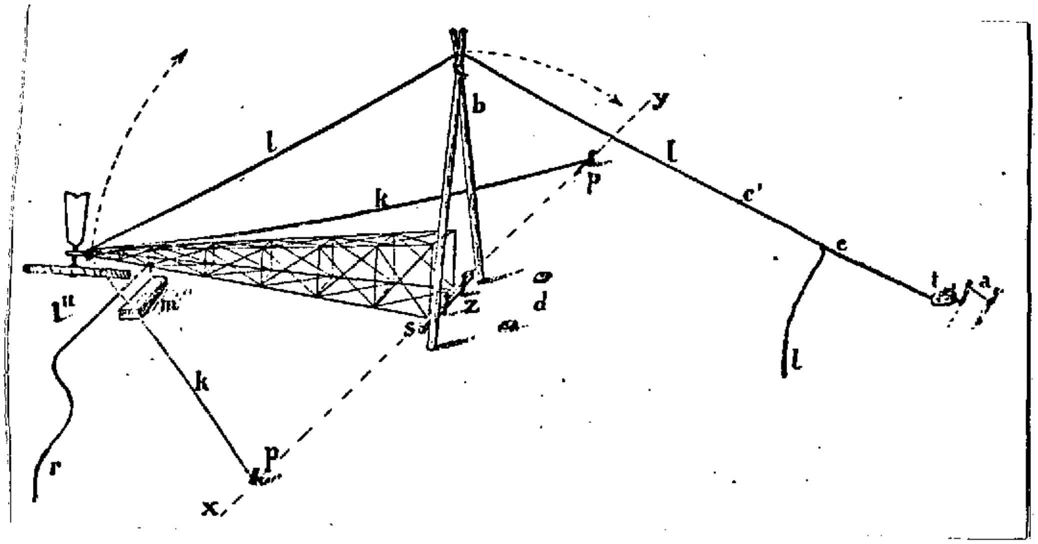

Fig. 145. Hoisting by crossed putlogs.

The chain c of the winch is moored to the hoisting cable ll and, if the chain c is not long enough for the entire hoisting distance, the excess of the cable ll is moored to stakes aa /186 and the chain c is then attached farther to the rear, at c', for example.

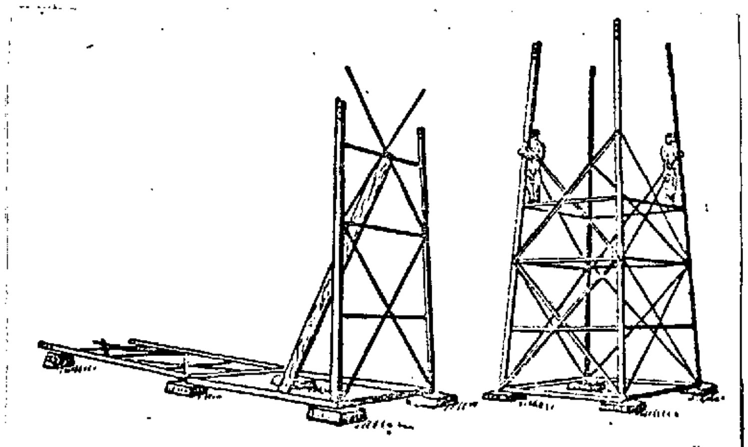

Fig. 146. Assembly by successive elements.

When the pylon has reached a sufficient angle, the putlogs b become useless and are removed, since the cable ll will be pulling directly on the pylon by this time.

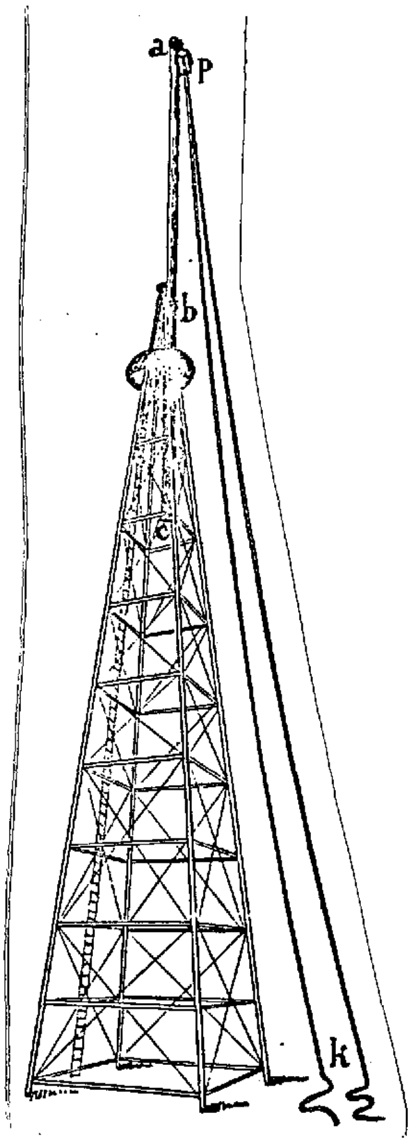

Fig. 147. Hoisting post for mechanism.

If the combined weight of the motor and the pylon seems to comprise too heavy a load for the hoisting equipment available, the pylon alone is set upright by one of the above procedures and the anchoring devices are secured. The motor is then mounted on the pylon by means of a pole b (Fig. /187
147) which is set upright within the pylon so that it will extend beyond the top of the pylon by 5 or 6 m.

A pulley or pulley-block is affixed to the top of this pole, and a cable k is passed over it, to be used to hoist all the elements of the motor and paddlewheel in succession. In this case it is a good idea to construct a fairly broad scaffold with horizontal putlogs and planks firmly attached to the uprights and cross-pieces of the pylon.

Finally, another method consists in assembling all the elements of the pylon vertically as shown in Fig. 146. For this purpose, if there are no scaffolding planks placed on the horizontal cross-beams, one can use ladders vertically secured to the uprights which have already been raised, and finally, the post shown in Fig. 147, to install the wind wheel. /188

Figs. 148 and 149 show the assembly of Adler wind motors by these procedures.

Reinforced Concrete Pylons (Fig. 142).

The dimensions of the steel longitudinal reinforcing irons must be computed for tension with total cross sections at least equal to those of the angle irons of a steel pylon with 4 or 6 legs.

In regard to compression, the cross section of the legs will be such that the stress on the concrete will not exceed 40 kg/cm^2.

Round Towers and Round Tanks

The pressure of the wind on these cylindrical surfaces should be estimated at half the pressure it would exert on a vertical rectangular cross section of the cylinder. This is because the wind slips over the round surface.

If the tower is masonry, the weight of this masonry will generally be sufficient to keep the assembly from turning over. However, if the tower is extremely high and its diameter is small, it is always a good idea to include round steel longitudinal reinforcing irons between the foundations and the masonry above the ground.

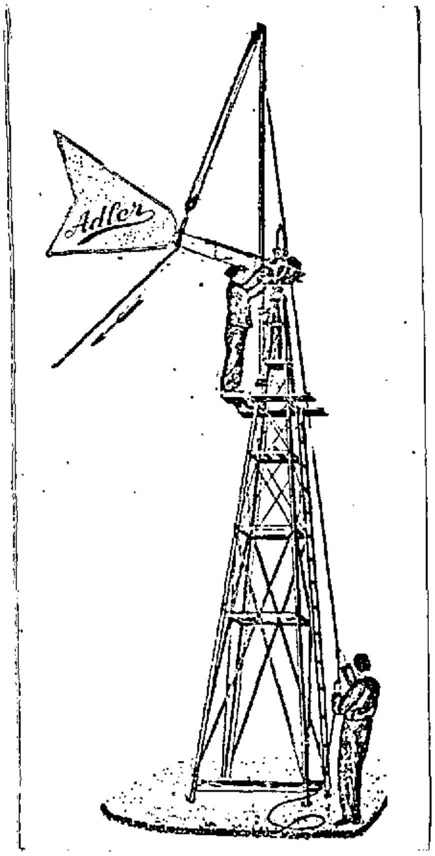

Fig. 148. Assembly of mechanism with re- straining cable.

With a thin-walled reinforced concrete tower, the steel reinforcing irons should have a total cross section at least equal to that of the four legs of a steel pylon computed as stated earlier.

(For the structure of these towers and pylons, see our book Béton Armé [Reinforced Concrete] and volume three of our Encyclopédie pratique du Bâtiment [A Practical Encyclopedia of Construction].)

Pylons and Tanks Constructed of Reinforced Blocks on Precast Concrete Blocks.

This method of construction offers the advantage of eliminating the considerable cost of the framing and scaffolding necessary with reinforced concrete rammed on the site.

The precast concrete blocks should be specially manufactured to fit into longitudinal reinforcing irons set up at the beginning of construction of the pylon and lateral reinforcing irons set in position as the courses are laid down. They should therefore have grooves to house these reinforcing irons.

Along these lines, we might mention the Monnoyer blocks, which are supplied in a thickness of only 10 cm and lengths which decrease from the bottom to the top of the tower. They also have the grooves necessary for effective insertion of the reinforcing irons.

Part b of Fig. 150 shows a horizontal half-section of a pylon constructed of blocks, in Remigny (Aisne), and part h, a half-section of the top of this pylon, One can see the shape /190 of the blocks and the satisfactory insertion of the longitudinal reinforcing irons.

This type of construction is performed without any scaffolding, placing a temporary plank on the courses which have already been laid down.

Fig. 151 shows a pylon of this type with a 300 m^3 tank, total height 20 m. The steel pylon of the windmill is embedded in the top of this pylon, as in Fig. 142. Access to the top of the tank is provided by a well left in the center of the tank and iron ladders to the ground.

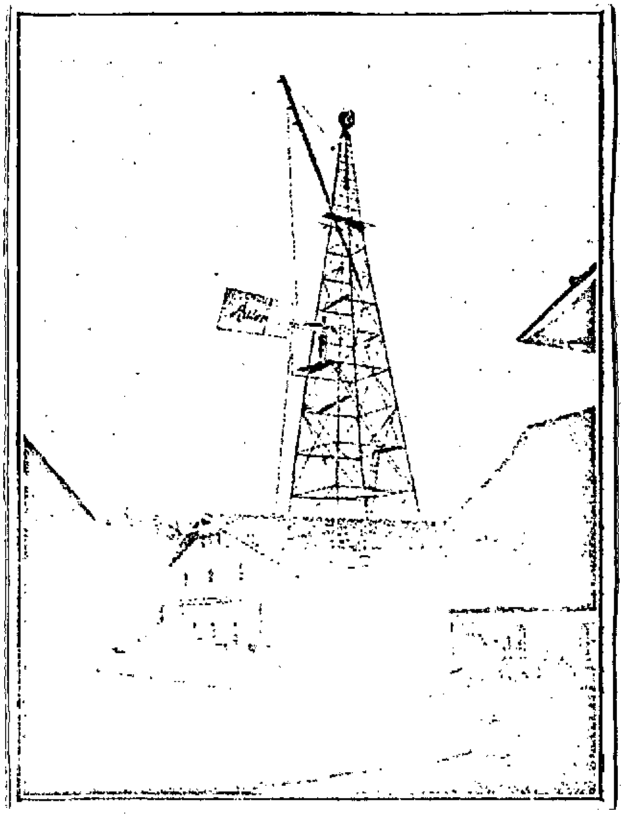

Fig. 149. Assembly of mechanism on a previously righted pylon.

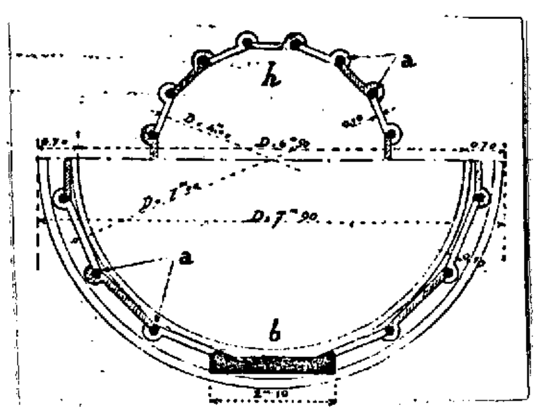

Fig. 150. Cross sections of a pylon constructed of reinforced concrete blocks.

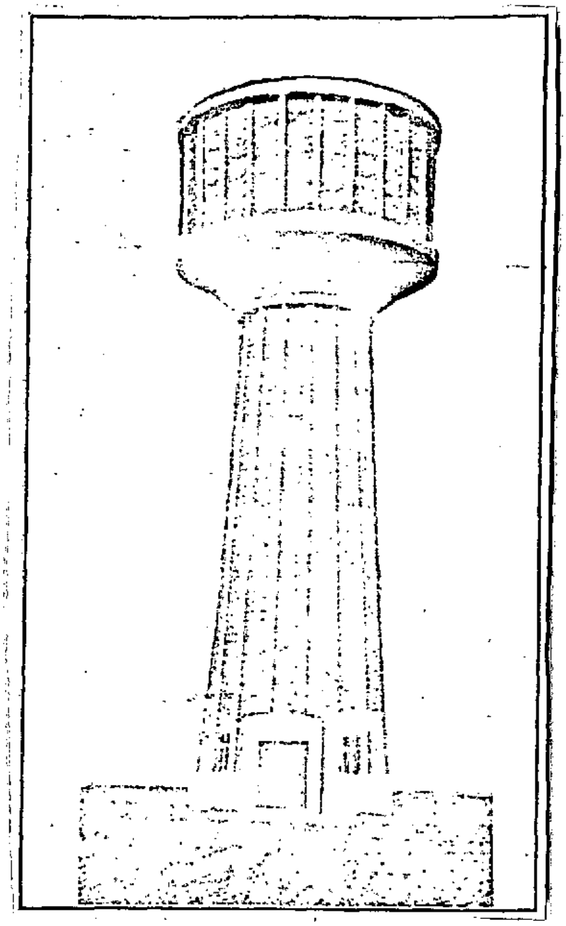

Fig. 151. Tank 20 m high, with a capacity of 300 m3, constructed of Monnoyer blocks.

Chapter 10

DRAWING AND RAISING WATER BY WIND MOTORS

Theoretically, a wind motor should be able to drive any type of hydraulic assembly; one need only install a suitable transmission system modifying the rotation speed between the drive unit and the user equipment. This problem was dealt with in Chapter 8 on transmission systems, which even gave a diagram for a centrifugal pump installation with vertical shaft for a deep well. /191

A complete report on all available systems of this type may be found in the Encyclopédie pratique des Constructeurs. Vol. 19, Pompes et Elévateurs de liquides [Pumps and Liquid Elevators]. (Price of this volume: 32 francs). However, some types of pumps and water elevators are generally used with wind motors, and these will be given special attention in the following discussion.

Rod-activated pumps

Siphon-pump

Used for low flow rates, this pump is characterized by its cylinder, which is always submerged, as shown in Fig. 152, preventing it from draining. This type is produced as a suction-pump alone or a suction- and force-pump, as shown here. /192

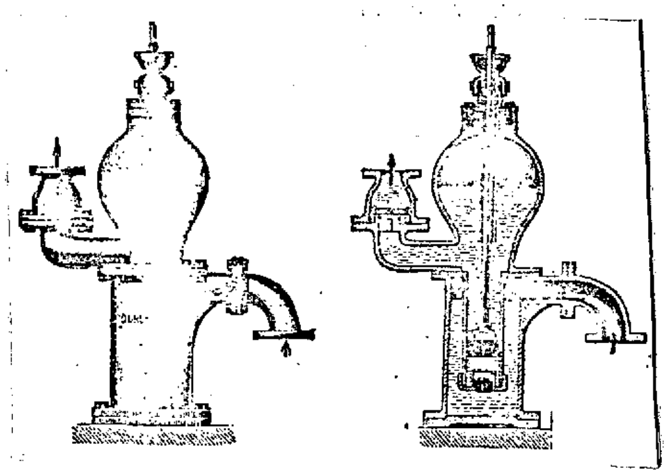

Fig. 152. Siphon-pump

Its characteristics, as given by Durey Sohy, are as follows:

SIPHON-PUMPS: DIMENSIONS AND FLOW RATES PER HOUR

Piston diam. mm	Diam. of pipes mm	Theoretical flow at 35 strokes per minute, in liters: Stroke 100 liters	Stroke 120 liters	Stroke 140 liters	Stroke 170 liters
60	40	655	775	905	1,090
70	40	869	1,060	1,240	1,500
80	40	1,050	1,265	1,475	1,800
90	50	1,325	1,575	1,850	2,250
100	60	1,640	1,955	2,290	2,775
110	60	1,995	2,395	2,795	3,380
120	70	2,375	2,835	3,320	4,030
130	70	2,775	3,320	3,885	4,705
140	80	3,235	3,885	4,515	5,500
150	80	3,695	4,430	5,165	6,280
160	80	4,200	5,040	5,880	7,140

These pumps are secured on the ground in plumb with the rod of the wind wheel.

Irrigation pumps

These are simple suction pumps in which the water flows through a galvanized steel spout. The cylinder is constructed of brass or pure copper and the piston of steel with leather fittings, with clack-valves.

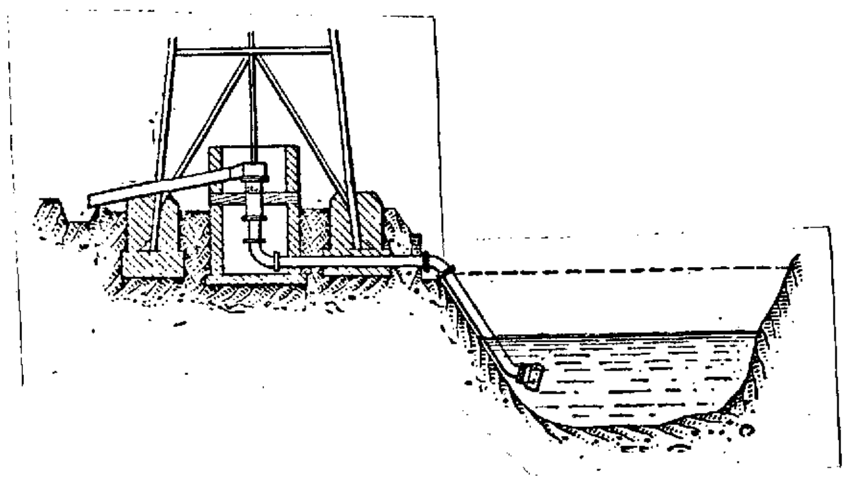

Fig. 153. Irrigation pump

For corrosive liquids, these pumps are constructed of special metals.

Fig. 153 shows one of these pumps (a Cyclone pump) installed; its characteristics are as follows.

THE "CYCLONE" IRRIGATION PUMP

Cylinder diam.	Diam. of suction pipe	Flow per hour in m^3, at 20 piston strokes per minute, with strokes of						
		120	160	180	240	320	400	500
200	100	4,5	6	6,6	9	12	15	18 8
250	125	7	9,4	10,5	14	18 8	23,5	29,6
300	150	10	13,4	15,1	20	26,8	33,6	42
350	175	13,8	18,4	20,7	27,6	36,8	46,1	57,7
400	200	18	24	27	36	48	60	75
450	225	22,8	30,4	34,2	45,6	60,8	76	95
500	250	28,2	37,6	42,3	56,4	75	94	117
600	300	40,7	54	61	81,4	107	155	169

These flows are theoretical and vary with the characteristics of the installation.

Differential pumps

Used for deep wells, these are single-effect pumps with suction only and double-effect pumps with suction and delivery. The wide-diameter fir wood piston displaces a large quantity of water into the pump chamber, resulting in a proportionate decrease in the weight of the rod of the wind motor.

The single-chamber models are driven directly by a rod serving as an extension of the wind motor rod; models with several chambers must be driven by rotary movement.

Fig. 154 shows a single-chamber model of this type of pump, with spherical bronze valves and a guiding mechanism for the piston rod. (Cyclone).

The following table gives the dimensions and capacities of this type of pump. /194

DIFFERENTIAL PUMPS

Diameter of pistons	Diameter of differential	Cross section of wood control rods	Diam. of iron pipe	Diameter of delivery pipe downstream from differential	Flow/hr at 22 piston strokes/min; stroke 400 mm
70	50	50× 50	80× 90	33×42	2,030 ℓ
85	60	50× 50	90×102	50× 60	2,990 —
95	70	60× 60	102×114	60× 70	3,690 —
105	70	60× 60	114×127	60×70	4,500 —
120	80	70× 70	127×140	66×76	5,900 —
145	90	80× 80	152×165	80× 90	7,920 —
160	110	80× 80	170×180	80× 90	10,500 —
200	130	100×100	210×222	102×114	16,500 —

These flow rates are theoretical and vary with the installation characteristics.

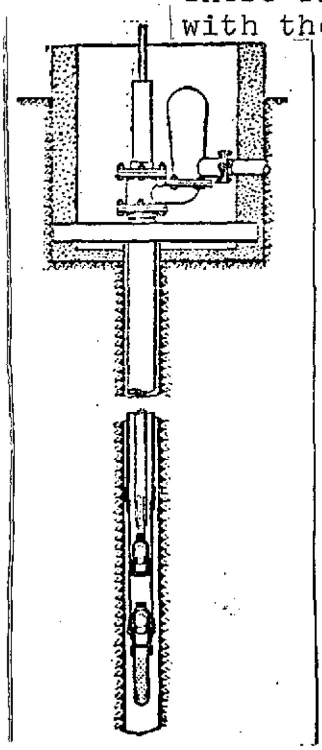

Fig. 154. Differential pump

Pumps driven by a backup motor when necessary

The piston rod of the pump may be connected directly to the extension rod of the wind motor by a keying system which can easily be disassembled, or it can be driven by a gasoline or electric motor, a belt transmission system using reduction gears or a perpetual screw, two rods and a cross-piece guided by vertical rods.

Fig. 155 shows a few examples of these mechanisms as designed by Friedrich Köster, for two small pumps installed on the ground and pump heads for deep wells or drills. The two rods of the reduction gear assembly need only be disconnected and keyed to the rod of the wind wheel.

Another procedure consists in placing two pumps side by side, as shown in Fig. 156 (Cyclone). One of the pumps is driven by the rod of the wind motor and the other by an auxiliary motor or transmission system; the latter is automatically stopped and started by a float.

Pumps driven by a rotating vertical shaft

The motion of the wind wheel is transmitted to a rotating vertical shaft which is connected to a transmission system enabling it to drive any type of pump. In this connection, see Chapter 8, "Transmission systems." /195

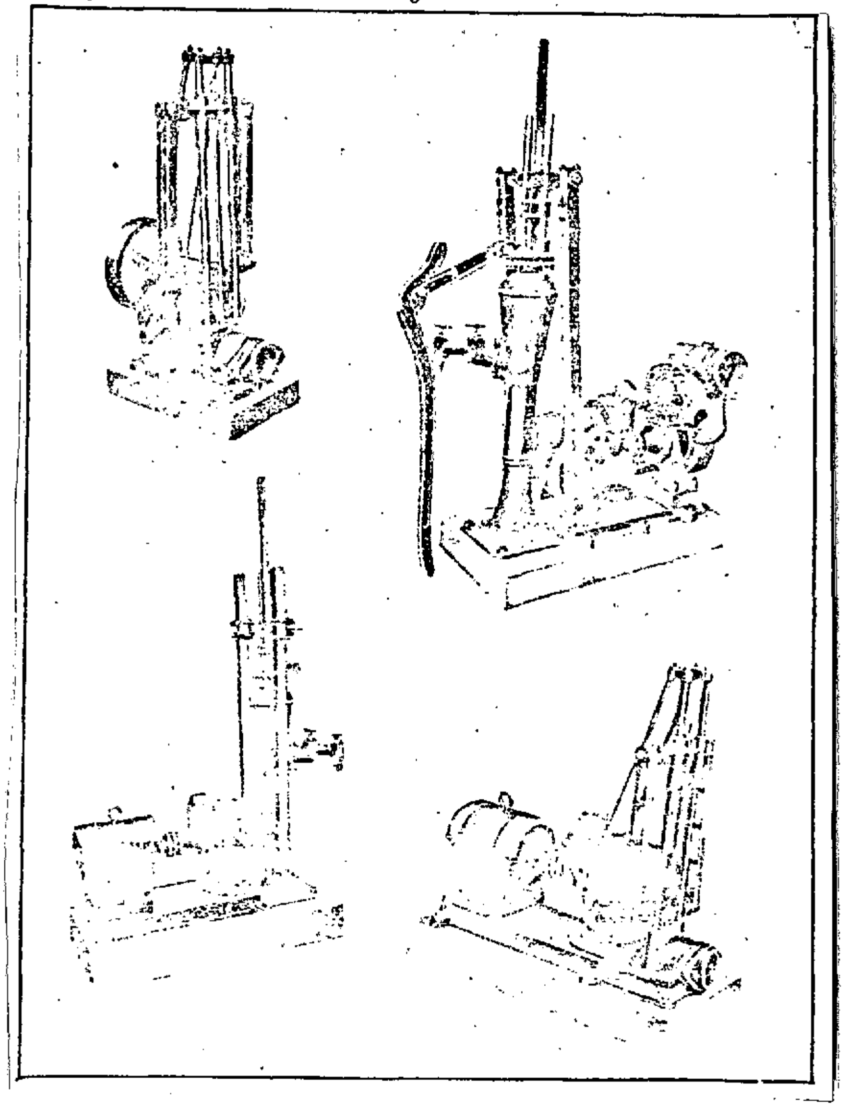

Fig. 155. Köster mechanisms for rod pumps

The following illustrations of installations of this type are given here:

Fig. 157: two differential pumps for deep wells driven by a gearbox with two parallel toothed wheels, placed outside the well (Adler Friedrich Köster). /196

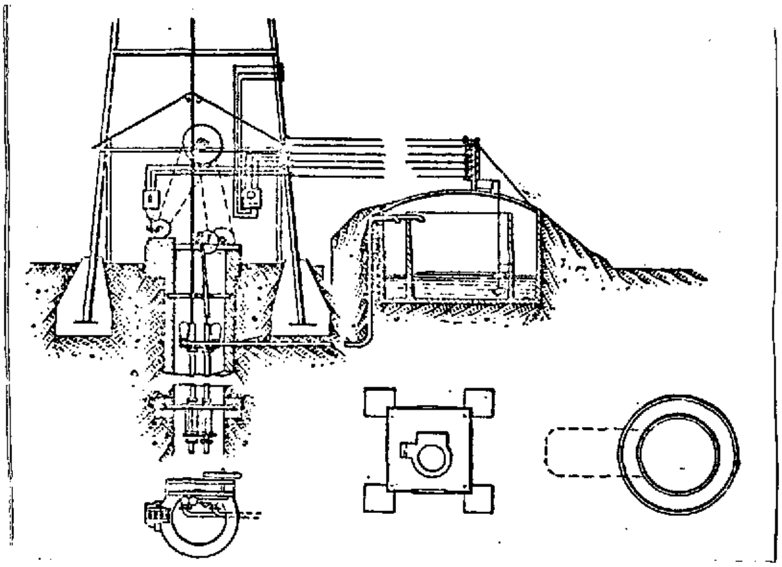

Fig. 156. Rod pump and electric backup pump

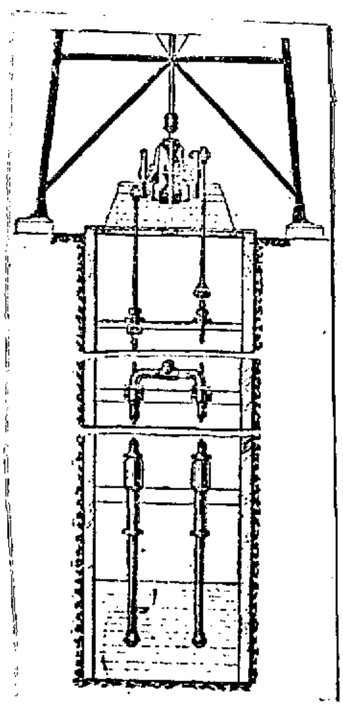

Fig. 157. Two differential pumps.

Fig. 158: a three-chamber pump installation with plunging pistons for elevating water to high levels of 25-200 m.

Fig. 159: a rotary pump installation supplying 3-20 m^3/hr, for irrigation of coffee or sugar cane plantations.

Fig. 117 shows the drive system for a vertical axis centrifugal pump for use in deep wells.

To drive piston pumps in deep wells, the moving head is frequently placed at the well opening at ground level and each piston is activated by a rod. It is an advantage to use differential pumps in this case, with the wooden rods floating in the water in the pump chamber (Fig. 154) and requiring no guidance within the well. /197

Pump driven by hydraulic transmission at a distance

The Cyclone Company of Compiègne has adapted the Mengin "hydropump" to its wind motors. This pump has a small piston driven directly by the rod of the wind wheel, which delivers water at high pressure into a cylinder containing another piston which drives the piston of the pump per se. The transmission is hydraulic, consisting of two small-diameter tubes whose

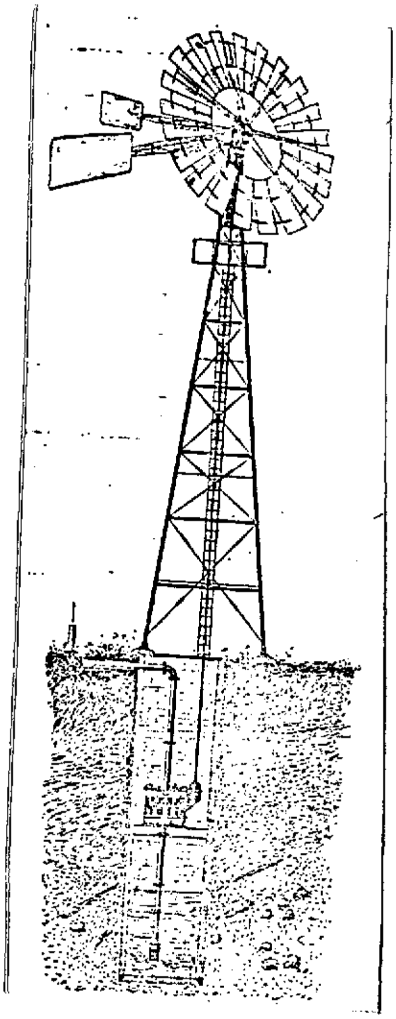

Fig. 158. Three-chamber pump in a well

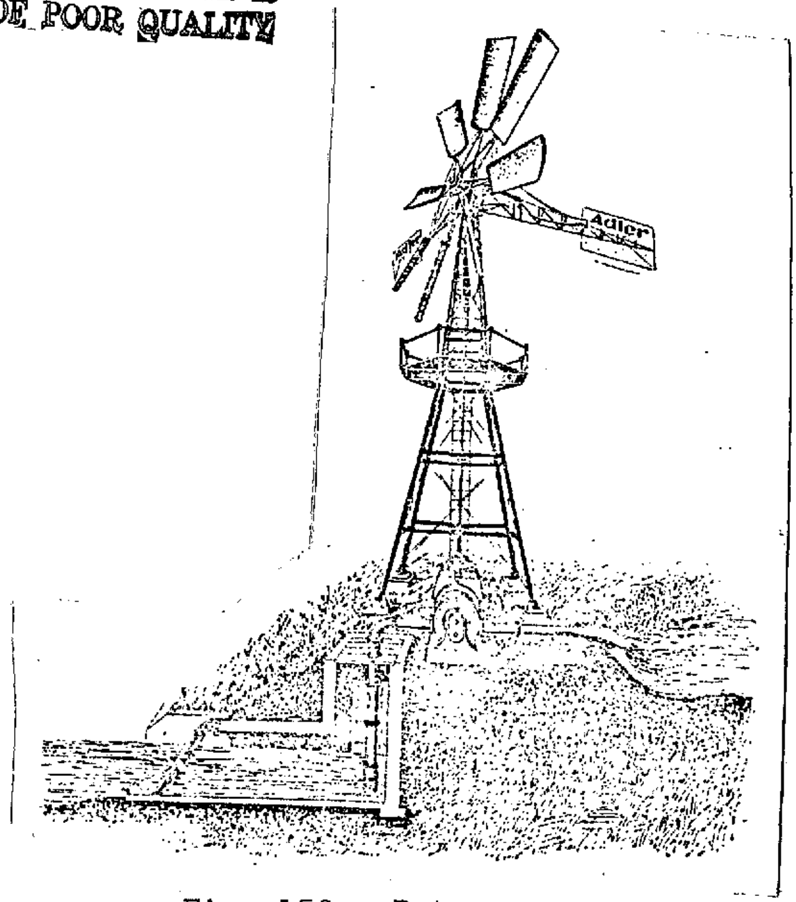

Fig. 159. Rotary pump

horizontal or vertical length may be as great as 200 m.

For a description of this pump, see Vol. 19 of our Encyclopedie pratique des Constructeurs, pages 134-136.

Applications of "Aermotors" /200

Community of Emanville

A wind motor 4.25 m in diameter on a pylon 16 m high. Depth of well: 31 m. The water is delivered to a 5 m^3 tank mounted inside the pylon.

This windmill replaced a horse-gear which required work by a man and a horse for five hours a day.

QUANTITIES OF WATER WHICH CAN BE ELEVATED BY "HERCULES" TURBINES UNDER WINDS OF APPROXIMATELY 5 m/sec WHICH ARE ESTIMATED TO OCCUR FOR SIX TO TEN HOURS PER DAY

Quantity of water raised in l/hr	Height of elevation in m									
	5	10	15	20	30	40	50	60	75	100
	Diameter of wind wheel in m									
400—500	2½	2½	2½	2½	3	3	3	3	3½	4
600—750	2½	2½	2½	2½	3	3	3½	3½	4	4½
800—1.000	2½	2½	3	3	3	3	3½	4	4½	5
1.200—1.500	3	3	3	3	3½	4	4	4½	5	5
1.700—2.000	3	3	3	3½	4	4½	4½	5	5	5½
2.200—2.500	3	3	3½	4	4½	5	5	5½	6	6
2.600—3.000	3	3	3½	4	4½	5	5	5½	6	6½
3.500—4.000	3	3½	4	4	5	5	5½	6	6½	7½
4.500—5.000	3	3½	4	4½	5½	5½	6	6½	7	8
5.500—6.000	3½	4	4½	5	5½	6	6½	7½	8	9
7.000—8.000	3½	4	5	5	6	6½	7½	8	9	10
9.000—10.000	3½	4½	5	5½	6½	7½	8	9	10	11
11.000—12.000	3½	5	5½	6	7	8	9	10	11	12
13.000—15.000	4	5	6	6½	7½	9	10	11	12	13½
16.000—20.000	4½	5½	6½	7	9	10	11	12	13½	15
21.000—25.000	5	6	7	8	10	11	12	13½	15	15
26.000—30.000	5	6½	7½	9	11	12	13½	15	15	—
35.000—40.000	5½	7½	9	10	12	13½	15	15	—	—

The farmers fill their buckets at the tank, while the excess water from the tank feeds a pond.

Community of Montchauvet (Seine-et-Oise)

A windmill 4.90 m in diameter mounted on a tank 12 m high. Depth of well: 43 m. Total height of elevation: 55 m. Population: 250. Rate of flow per hour: 3,000 l. Rate of flow per day: approximately 25 m^3.

The windmill furnishes the entire water supply for this community ten months out of the year (Fig. 142).

Sächsische Stahl-Vindmotoren-Fabrick, G.R. Herzog, Dresden (Germany)

ELEVATION OF WATER

Height of elevation:	2½	5	10	15	20	25	30	40	50	60	70	80	90	100
Wheel diameter:	Quantity of water raised per hour in liters													
2.0 m	1,300	900	450	250	200	170	150	100	80	70	65	60	50	40
2.5 m	2,500	1,900	1,200	1,050	950	800	600	400	350	300	200	180	150	130
3.0 m	8,800	7,500	4,000	2,200	2,000	1,750	1,300	1,000	700	650	450	400	350	300
3.5 m	19,500	15,500	6,500	4,100	2,700	2,400	2,000	1,309	1,100	1,000	850	700	650	500
4.0 m	28,000	19,500	10,400	5,800	5,200	3,400	2,600	2,000	1,700	1,400	1,250	1,000	800	650
4.5 m	40,000	26,000	13,500	9,100	6,500	5,200	4,200	2,600	2,400	2,000	1,700	1,400	1,200	1,000
5.0 m	67,000	32,500	20,000	13,000	10,400	8,100	6,000	5,200	3,200	2,900	2,600	2,400	2,000	1,600
5.5 m	91,000	40,000	26,000	17,000	13,000	11,000	7,800	6,300	4,600	4,000	2,900	2,800	2,650	2,400
6.0 m	100,000	50,000	36,000	27,000	22,000	14,300	13,500	8,200	6,700	6,300	5,400	5,000	4,250	3,900
6.5 m	140,000	63,000	47,000	40,000	33,000	22,000	19,000	12,000	9,300	8,500	6,400	6,000	4,900	4,300
7.0 m	195,000	78,000	52,000	44,000	35,000	25,000	21,000	13,000	9,700	9,000	7,600	6,400	5,600	4,900
7.5 m	210,000	92,000	55,000	39,700	38,000	32,000	28,000	13,500	11,000	9,700	9,000	7,300	6,300	5,800
8.0 m	223,000	111,800	64,000	48,000	46,000	35,000	32,000	15,000	13,500	11,000	10,000	9,400	7,200	6,600
8.5 m	270,000	140,000	78,000	53,000	50,000	38,000	36,000	19,500	15,500	14,000	11,500	11,000	9,000	7,300
9.0 m	310,000	186,000	90,000	67,500	57,000	42,000	39,000	23,000	19,500	15,500	14,000	12,000	10,800	9,500
10.0 m	365,000	210,000	120,000	83,500	60,000	49,500	43,000	30,000	23,000	20,000	16,000	14,500	12,100	10,000
11.0 m	410,000	240,000	165,000	120,000	82,500	67,500	45,000	37,500	30,500	23,000	20,000	16,500	13,700	12,800
12.0 m	470,000	310,000	200,000	150,000	105,000	82,500	60,000	45,000	38,000	30,500	24,000	22,000	18,000	16,000

During two months, July and August, it is necessary to use an electric backup motor. Nevertheless, the saving in fuel is estimated at 6,000 francs per year.

Since the total installation costs of the windmill were 32,000 francs, the community is making a considerable savings on the amortization of the assembly.

Community of Sorneville (Meurthe-et-Moselle)

A wind motor 4.90 m in diameter mounted on a pylon 24 m high. The water is poured into a sump 1.50 m deep and delivered to a tank located 650 m away and 33 m above the suction line.

This wind motor has permitted virtually complete elimination of the use of a 3 hp electric pump operating seven hours a day.

Elevation of water by the Bollée windmill /201

Results of tests performed in Frémicourt (Pas-de Calais) on September 26, 1928

Diameter of wind turbine: 7 m.
Three-chamber pump: 350 x 100.
Level of elevation: 44 m, taking the loss of head into account.

Test No. 1 (8:55 to 9:55 a.m.)

Water raised............................8.300 m^3
Average wind............................4.32 m/sec
Minimum wind............................2.30 m/sec
Maximum wind............................7.10 m/sec

Test No. 2 (10:51-11:51 a.m.)

Water raised............................10.300 m^3
Average wind............................4.86 m/sec
Minimum wind............................3.00 m/sec
Maximum wind............................7.00 m/sec

Test No. 3 (2:44 to 3:44 p.m.)

Water raised............................10.880 m^3
Average wind............................ 4.93 m/sec
Minimum wind............................ 2.83 m/sec
Maximum wind .... 6.83 m/sec

Test No. 4. (4:17 to 5:17 p.m.)

Water raised.........................12.600 m3
Average wind......................... 5.43 m/sec
Minimum wind......................... 3.00 m/sec
Maximum wind......................... 7.16 m/sec

These tests were witnessed by E. C. P. Engineers Courtot and Ronfort, the originators of the water supply project for the community of Frémicourt.

<u>Results of tests performed at Marquion (Pas-de-Calais) on January 31, 1929.</u>

Diameter of wind turbine: 7 m.
Three-chamber Bollée pump: 400 x 85.
Level of elevation: 28 m, taking the loss of head into account.

Test No. 1

Water raised...................14.600 m3
Average wind................... 5.05 m/sec
Minimum wind................... 2.66 m/sec /202
Maximum wind................... 7.66 m/sec

Test No. 2

Water raised....................3.260 m3
Average wind....................3.15 m/sec
Minimum wind....................2.00 m/sec
Maximum wind....................4.30 m/sec

Test No. 3

Water raised...................21 m3
Average wind................... 5.76 m/sec
Minimum wind................... 5.00 m/sec
Maximum wind................... 7.16 m/sec

<u>Results of tests performed at Blairville (Pas-De-Calais) on August 26, 1930.</u>

Diameter of wind turbine: 5 m.
Three-chamber Bollée pump: 320 x 80
Level of elevation: 55 m, taking the loss of head into account.

Test No. 1

Water raised.................3.580 m^3/sec
Average wind................. 4.38 m/sec
Minimum wind................. 6.33 m/sec
Maximum wind................. 2.33 m/sec

Test No. 2

Water raised.................. 9.865 m^3
Average wind.................. 6.33 m/sec
Minimum wind.................. 8.00 m/sec
Maximum wind.................. 4.00 m/sec

Test No. 3

Water raised.................. 5.939 m^3
Average wind.................. 5.44 m/sec
Minimum wind.................. 7.66 m/sec
Maximum wind.................. 3.50 m/sec

Test No. 4

Water raised.................. 3.580 m^3
Average wind.................. 4.34 m/sec
Minimum wind.................. 6.16 m/sec
Maximum wind.................. 2.15 m/sec

Assemblies used with windmills for irrigation and draining of swamps

These assemblies, which are generally of extremely simple and durable construction, are specially designed to handle large quantities of water, several thousand cubic meters per hour, raised to a low level of only a few meters. The most frequently used assemblies will be mentioned here.

Inclined chain-pump (Fig. 160)

This type of pump consists of a series of paddles attached to an endless chain, moving inside a wooden or sheet metal /208
channel or trough forming an angle of 30-40° with the horizon.

The height of the paddle should be between 1/2 and 4/5 its length; 4-5 mm of play is left between the side edges of the paddles and the trough.

The spacing between the paddles is one to one and one-half times their height and their approximate rate of travel is 1.50 m/sec.

Efficiency approximately 60%.

Vertical chain-pumps, norias, and bucket-chains

These assemblies are suitable for elevating water to levels of 5-30 m. In all, the chain-pump assemblies, the flow rate per minute is equal to the quantity of water carried by a paddle or bucket multiplied by the number of paddles passing point a or g in one minute (Fig. 161).

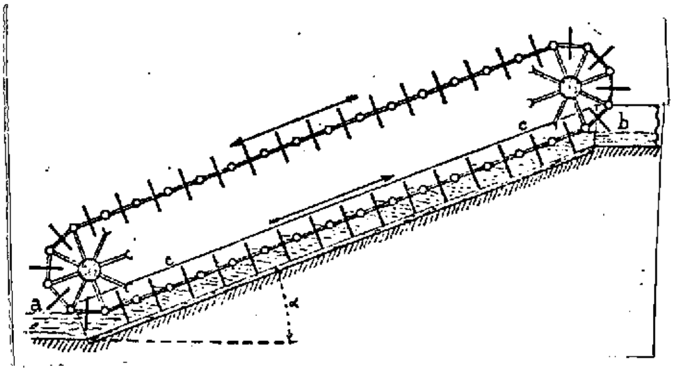

Fig. 160. Inclined chain-pump.

Paddle wheel (Fig. 162)

These elevating wheels operate in the same way as an inclined chain-pump, but their paddles move in a circular channel. The efficiency may reach 82% and is estimated to be consistently higher than 75%; the amount of water raised may be as much as several thousand cubic meters per hour. The peripheral speed of the wheel should not exceed 1 m/sec. The water can be raised to a level of 3-4 m, with the diameter of the wheel to the ends of the paddles being 2.5 to 3 times the level of elevation of the water.

Drum wheels (Fig. 163, vertical cross section)

This type of wheel consists of two wooden or sheet metal discs with several helicoidal partitions between them; the /204
water leaves the wheel close to the shaft through outlets machined into one or both of the discs. Maximum efficiency is 82%.

Débauve mentions one of these wheels, 10.50 m in diameter, raising 10 m^3 of water per minute to a height of 4.60 m.

J. Claudel mentions one assembly 7 m in diameter and with an internal width of 1 m, with two spirals, dipping into the water to a depth of 1 m and operating at 10 rpm, which raised 2,400 m^3 of water per hour to a height of 2 m. The designer, /205
Cavé, has designed several large drums for drawing water; these have four partitions forming an Archimedes' spiral or two partitions whose turns approach the center more rapidly than in an Archimedes' spiral, with the result that the surface of the trapped water is constantly tangent to the upper turn.

The more the drum dips into the water, the greater the amount of water raised.

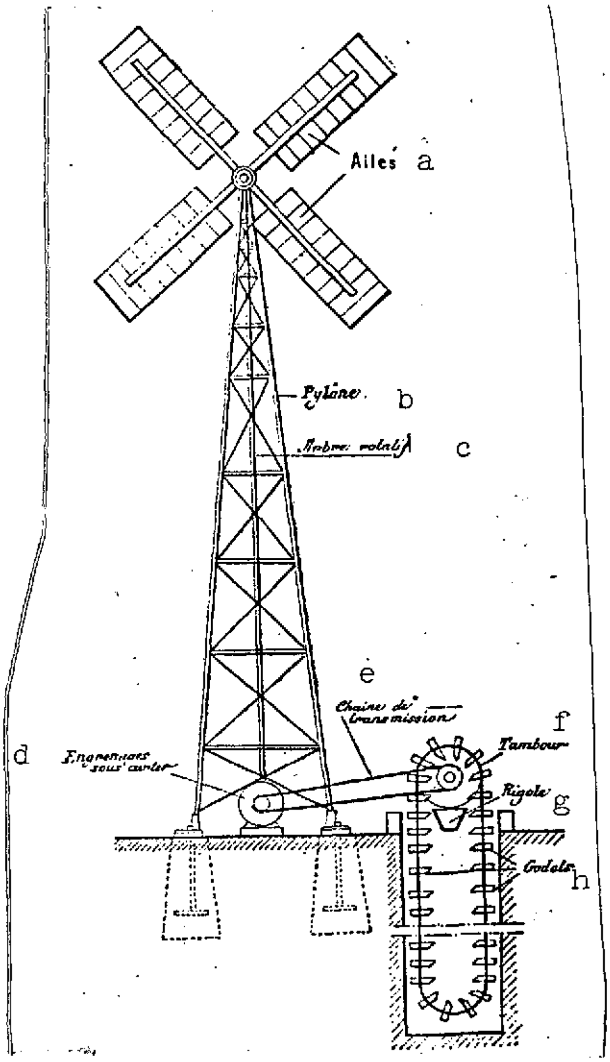

Fig. 161. Driving a noria

Key: a. vanes
b. pylon
c. rotating shaft
d. gears in gearbox
e. transmission chain
f. drum
h. buckets

Fig. 164 shows a drum wheel 5 m in diameter elevating 2,000 m^3 of water /206 per hour to a level of 1.20 m, connected to a Cyclone wind motor. The wind wheel is 12 m in diameter and is installed on a pylon 10 m high.

Archimedes' screws

Archimedes' screws may be used to advantage for raising water by windmills when the difference between the downstream and upstream levels does not exceed 3.50 m (draining of swamps or irrigation).

The table below gives the diameters, speeds, flow rates and power consumed by the assemblies constructed by the Lykkegaard Wind-Mill Manufacturing Company. These were built up to a diameter of 2.5 m for a flow rate of 4,000 m^3/hr.

Fig. 165 shows one of /207 these screws driven by a vertical-shaft wind motor. Here the axis of the screw makes a 30° angle with the horizon, but this may be as high as 45°.

The constructors state that the angle made by a tangent to the spiral of the screw plotted on the core with the generatrix of this core or axis ranges from 45-60°.

Generally, three parallel and equidistant spirals are placed on the same core.

Some designers replace the cylinders completely enclosing the spiral, termed the "barrel," with a fixed semicircular

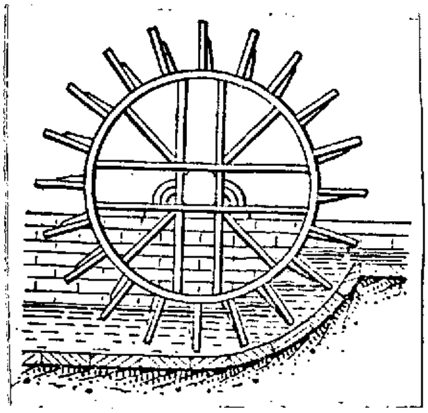

Fig. 162. Paddle-wheel (See Fig. 5)

cement masonry or sheet metal channel.

J. Claudel gives the following results obtained by Lamandé with an Archimedes' screw:

Length of screw....... 5.85 m
Outside diameter...... 0.49 m
Angle of shaft
  with horizon........ 35°
Rpm of screw.......... 40
Level of elevation
  of water............ 3.50 m
Amount of water
  raised per hour to 3.30 m:
  45 m3

Diam. of screw in mm	Rpm	Flow rate in m/sec	Power in hp/m of elevation of water
350	110	21	0.49
450	83	36	0.81
550	72	53	1.22
650	62	74	1.68
750	55	98	2.21
850	50	126	2.84
1,000	42	175	3.90
1,100	38	212	4.73
1,200	35	252	5.63
1,300	32	296	6.62
1,400	30	344	7.65
1,500	28	394	8.75
1,600	26	448	10.00
1,700	24.5	507	11.30
1,800	23	568	12.63
1,900	22	634	14.15
2,000	21	702	15.60
2,100	20	770	17.15
2,200	19	846	18.87
2,300	18	930	20.60
2,400	17.5	1,010	22.50

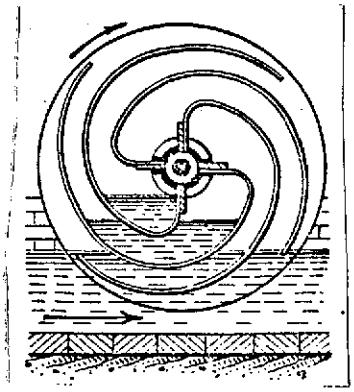

Fig. 163. Drum

The speed of 40 rpm is too low for the efficiency to be very high. This screw was driven by two crews of nine men, each working in two-hour shifts, and the work performed per man was 16.50 m3 elevated to a height of 1 m. /208

According to the Danish table given above, if the rotation speed had been 80 rpm the yield would have been much higher.

The Etablissements Chêne of Saint-Quentin have prepared the following table for raising water to levels of 1, 2 and 3 m by means of an Archimedes screw and a wind motor.

Diameter of screw	Flow rate in 1/min	Wheel diam. required for elevation to a height of:		
		1 meter	2 meters	3 meters
0.35 m	1,000	4.00 m	5.00 m	6.00 m
0.40 m	2,000 —	4.50 m	6.00 m	7.00 m
0.50 m	3,000 —	5.50 m	7.50 m	9.00 m
0.60 m	4,000 —	6.50 m	9.00 m	10.00 m
0.70 m	5,000 —	7.00 m	10.00 m	11.00 m
0.80 m	6,000 —	8.00 m	11.00 m	12.00 m
0.90 m	7,500 —	9.00 m	12.00 m	»
1.00 m	9,000 —	10.00 m	»	»
1.20 m	13,000 —	11.00 m	»	»
1.40 m	18,000 —	12.00 m	»	»

These flow rates, furnished by the designers of the Agricco assembly, are almost double those of thin-bladed windmills. We are reproducing them here without any guarantee of their accuracy. /216

Automatic regulators with float

These assemblies are used in some water-drawing installations to stop the wind motor, and the pump as a result, when the tank is full. A wide variety of devices may be used for this purpose; the following discussion will include two which have

/205

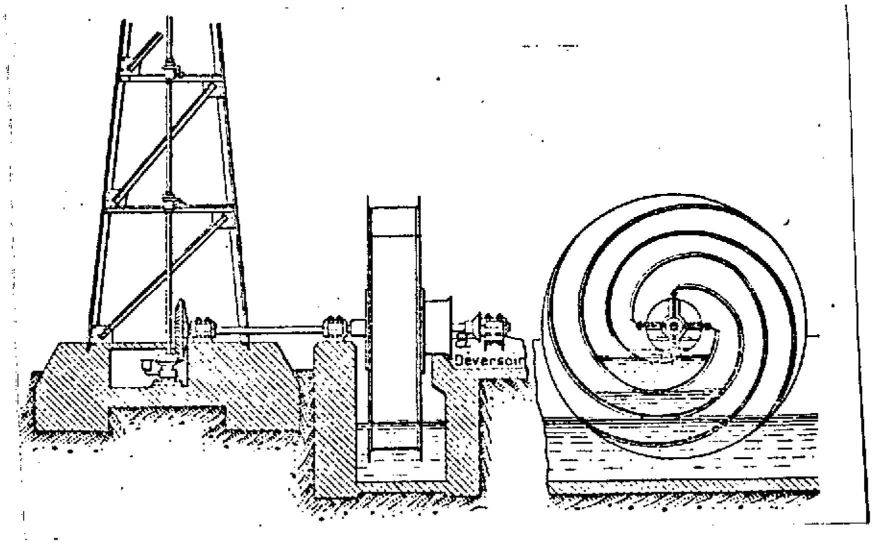

Fig. 164. A drum installation

Key: a. Weir

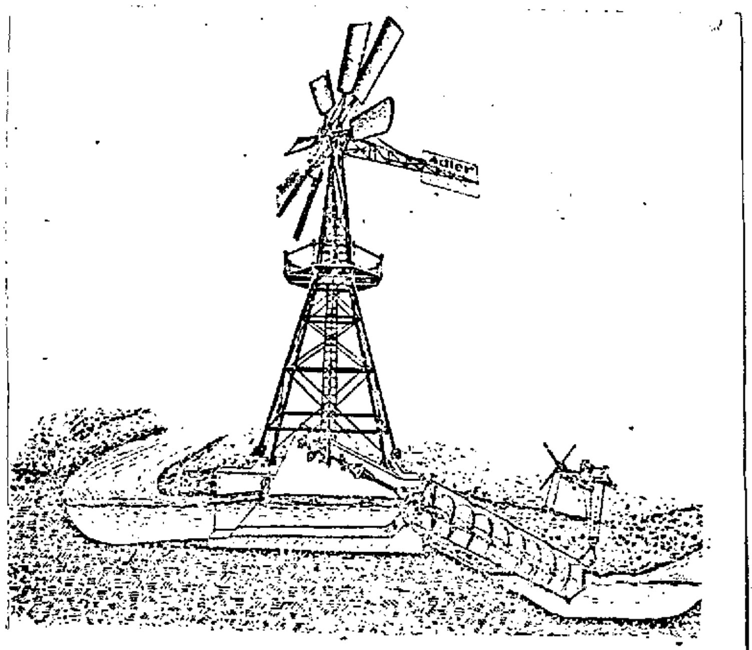

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Fig. 165. Archimedes' screw with winch to vary the level of immersion, driven by a universal joint

MANUFACTURERS' TABLES ON RAISING WATER BY WIND MOTORS

COMPARATIVE TABLE, PREPARED BY THE AERMOTOR COMPANY, OF THE COST PRICES OF MOTORS DRIVING A PUMP WITH A FLOW RATE OF 2,000 ℓ/hr AND OPERATING 8 HOURS PER DAY TO FURNISH A DAILY FLOW RATE OF 16,000 ℓ (HEIGHT 30 m)

	1 hp explosion engine	day	year	1 hp electric motor	day	year	AERMOTOR 3.65 m in diameter	year
Motive power	1/2 ℓ gasoline/ hr/day at 2 [illegible] F/ℓ	8.00	2,920	8.6 hW/hr, that is 68.8 hW for 8 h, at 0.175 F	11.94	4,358	Wind	0
Lubrication	1/15 ℓ oil, that is, 8/15ths for 8 h at 5 F/ℓ	2.66	970	6 ℓ at 6 F		36	12 ℓ at 5.60 F	67
Labor	Starting, stopping, supervision 1 h at 2 F/h	2	730	Starting, stopping, supervision 1/2 h at 2 F/h	1	365	Oil change once a year 1 h at 2 F/h	2
Maintenance and repairs			150		75			25
Cost price per year			4,770			4,834		94

This is not to mention amortization, which for the Aermotor is completed in a few decades

COST PRICE TABLE, PREPARED BY THE CYCLONE COMPANY, FOR THE ELEVATION TO A LEVEL OF 25 m OF 10,000 ℓ OF WATER PER DAY, THAT IS, 2,000 ℓ/hr FOR 5 h

	Electric motor			Gasoline engine			Cyclone wind motor	
		per day	per year		per day	per year		per year
Motive power	1/2 hp, or 400 W for 6 h 2 kW at 1.50 F	3	1,080	1 hp, that is, 1/2 ℓ gas./hr for 5 h, 1-1/2 ℓ at 1.50 F	4.50	1,620		
Lubrication	4 ℓ oil at 4 F		16	1/3 ℓ oil at 4 F	1.20	432	10 ℓ oil at 4 F	40
Labor, starting stopping, monitoring		0.50	180	3/4 h at 2 F	1.50	540	Oil change	6
Maintenance			40			150		50
	Total per year		1,316	Total per year		2,742	Total per year	96

WIND MOTORS DESIGNED BY HENRY OF BOULOGNE-SUR-SEINE

Diameters...	2.55 m	3 m	3.60 m	4.20 m	4.80 m	5.40 m	6 m
Power in hp ...	1/8	1/4	1/2	3/4	1 1/2	2 1/4	3
Quantities of water raised per hour under a 10 m/sec wind							
To 5 m	1,600 ℓ	4,000 ℓ	6,500 ℓ	9,000 ℓ	16,000 ℓ	25,000 ℓ	32,000 ℓ
To 10 m	800 —	2,000 —	3,200 —	4,500 —	9,000 —	12,000 —	15,000 —
To 20 m	—	1,000 —	1,600 —	2,200 —	4,000 —	6,000 —	6,500 —
To 40 m ...	—	—	—	1,100 —	1,800 —	3,000 —	3,000 —
To 60 m	—	—	—	—	1,200 —	1,800 —	2,000 —

GENERAL TABLE OF FLOW RATES AND PUMPS TO BE USED WITH EACH "AERMOTOR" DEPENDING ON THE LEVEL OF ELEVATION

Level of elevation in meters	1.85 m Aermotor			2.45 m Aermotor			3.05 m Aermotor			3.65 m Aermotor			4.25 m Aermotor			4.90 m Aermotor		
	Caliber of pump in mm	Caliber of piping in mm	Flow rate in l/h	Caliber of pump in mm	Caliber of piping in mm	Flow rate in l/h	Caliber of pump in mm	Caliber of piping in mm	Flow rate in l/h	Caliber of pump in mm	Caliber of piping in mm	Flow rate in l/h	Caliber of pump in mm	Caliber of piping in mm	Flow rate in l/h	Caliber of pump in mm	Caliber of piping in mm	Flow rate in l/h
5	100	50/60	2.300	120	60/70	4.850*	150	80/90	8.350	200	102/114	15.000	250	250	23.100	300	300	30.000
10	70	40/49	1.100	80	40/49	2.150	100	50/60	3.700	130	66/76	6.400	175	102/114	11.300	200	102/114	13.000
15	60	33/42	800	65	33/42	1.400	80	40/49	2.350	110	60/70	4.600	130	66/76	6.250	175	102/114	10.000
20	50	33/42	550	60	33/42	1.200	70	33/42	1.800	100	50/60	3.800	110	60/70	4.450	150	80/90	7.600
25				60	33/42	1.200	65	33/42	1.550	90	50/60	3.000	110	60/70	4.450	140	80.90	6.600
30				50	33/42	830	60	33/42	1.300	80	40/49	2.400	100	50/60	3.700	130	72/82	5.700
35				50	60/70	830	60	72/82	1.300	70	80/90	1.850	90	102/114	3.000	120	127/140	4.800
40				40	50/60	530	50	60/70	920	65	72/82	1.600	90	102/114	3.000	120	127/140	4.800
45							50	60/70	920	65	72/82	1.600	80	90/102	2.350	120	127/140	4.800
50							40	50/60	580	60	72/82	1.350	80	90/102	2.350	110	127/140	4.000
60										50	60/70	950	70	80/90	1.800	110	115/127	4.000
70										50	60/70	950	65	72/82	1.550	100	115/127	3.300
80	Deep well									40	50/60	600	60	66/76	1.300	90	102/114	2.700
90													60	66/76	1.300	80	90/102	2.150
100													50	60/70	920	80	90/102	2.150
120													40	50/60	580	70	80/90	1.650
140																60	66/76	1.200
160																50	69/70	830

*Periods in this table should be read as commas. -- Trans.

The above table shows the approximate flow rates for Aermotors under winds of 7-9 m/sec.

The choice of pumps should be made in conformity with the data given above. Never use piping with a lower caliber than that indicated. For levels of elevation higher than 35 m, use special pumps for deep wells.

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TABLE OF AVERAGE FLOW RATES IN l/h OBTAINED WITH FIVE TYPES OF "AERMOTOR" IN 7 m/sec WINDS

Level of elevation

Diameter of turbine	5 m	10 m	15 m	20 m	30 m	50 m	80 m	100 m	120 m
2.45 m	4,850	2,150	1,400	1,200	830				
3.05 m	8,350	3,700	2,350	1,800	1,300	930			
3.65 m	15,200	6,400	4,600	3,850	2,400	1,600	600		
4.25 m	23,100	11,300	6,250	4,450	3,700	3,000	1,300	900	580
4.90 m	30,000	13,500	10,300	7,600	5,700	4,800	2,700	2,150	1,650

APPROXIMATE FLOW RATE OF "AERMOTORS" IN m^3 PER DAY

Level of elevation	Diameter of turbine				
	2.45 m	3.05 m	3.65 m	4.25 m	4.90 m
2.50 m	90 m^3	158 m^3	290 m^3	440 m^3	600 m^3
5.00 m	45 m^3	79 m^3	145 m^3	220 m^3	300 m^3
10.00 m	20 m^3	35 m^3	61.5 m^3	105.5 m^3	130 m^3
15.00 m	13 m^3	22.5 m^3	45 m^3	55 m^3	99 m^3
30.00 m	8 m^3	12.5 m^3	23.5 m^3	35 m^3	55 m^3
80.00 m	—	—	6.5 m^3	12.5 m^3	23 m^3

OUTPUT OF HORIZONTAL-SHAFT WIND MOTORS IN 10 m/sec WINDS (AFTER PLISSONNIER)

Diameter of turbine	Power in hp	Quantity of water raised to a level of 10 m in m^3/h
2.50 m. ...	1/8	0.800
3.00 m. ...	1/4	2.000
3.60 m. ...	1/2	3.200
4.70 m. ...	3/4	4.500
4.80 m. ...	1 1/2	9.000
5.40 m. ...	2 1/4	15.000
6.00 m. ...	3	25.000
7.00 m. ...	4 1/2	40.000
8.00 m. ...	5	47.000
9.00 m. ...	6	55.000
10.00 m. ...	7	64.000

TABLE PREPARED BY THE ÉTABLISSEMENTS CHÊNE OF SAINT-QUENTIN GIVING THE DIAMETERS OF "ZÉPHIR" WIND MOTOR WHEELS WITH DIRECT TRANSMISSION TO A PISTON PUMP BY ROD AND CRANKSHAFT

Diameter of piston in mm.	Flow rate per h	Total level of elevation of water in m											
		5	10	15	20	25	30	35	40	45	50	55	60
62	750	3	3	3	3	3	3	3	3,5	3,5	3,5	3,5	3,5
70	900	3	3	3	3	3	3	3,5	3,5	3,5	3,5	4	4
80	1.200	3	3	3,5	3,5	3,5	4	4	4	4	4,5	4,5	4,5
100	1.800	3	3,5	3,5	3,5	4	4	4,5	4,5	4,5	4,5	5	5
120	2.500	3	3,5	4	4	4	4,5	4,5	4,5	5	5	5,5	5,5
150	3.800	3,5	4	4	4,5	4,5	5	5	5,5	5,5	6	6	6,5

The data in this table correspond to wind speeds of 4-5 m/sec, which are the most frequent in occurrence in northern France.

APPROXIMATE FLOW RATE OF WATER PER DAY FURNISHED BY "AGRICCO" THICK-VANED WINDMILLS

Level of elevation	Type and diameter of "Agricco" turbine					
	A-1 5 m.	A-2 6.50 m	A-3 7.70 m	A-4 10 m	A-5 11 m	A-6 12.50m
2.50 m	1.140 m^3	2.000 m^3	2.880 m^3	4.000 m^3	6.000 m^3	9.600 m^3
5.00 m	570 m^3	1.000 m^3	1.440 m^3	2.000 m^3	3.000 m^3	4.800 m^3
10.00 m	280 m^3	500 m^3	720 m^3	1.000 m^3	1.500 m^3	2.400 m^3
15.00 m	190 m^3	330 m^3	480 m^3	660 m^3	1.000 m^2	1.600 m^3
30.00 m	100 m^3	170 m^3	240 m^3	330 m^3	500 m^3	800 m^3
50.00 m	60 m^3	100 m^3	150 m^3	200 m^3	300 m^3	480 m^3

[In both the above tables, periods should be read as commas and commas as periods. -- Trans.]

been described to us by Goold Shapley and Muir Company, Brantford, Canada.

1. Regulator with mechanical transmission (Fig. 166). A fairly large and heavy float f dips into the water tank b. Through cables and a return lever l, this float communicates its motion to a catch which locks into a rachet-wheel r when the float f is lifted by the water entering through the top of the tank b. When the catch and the rachet-wheel have locked, /217
the lever u, which is connected by a cable to the rod t of the pump, activates a sort of differential pulley bearing a counterweight p and a cable h which keeps the wind wheel facing into the wind.

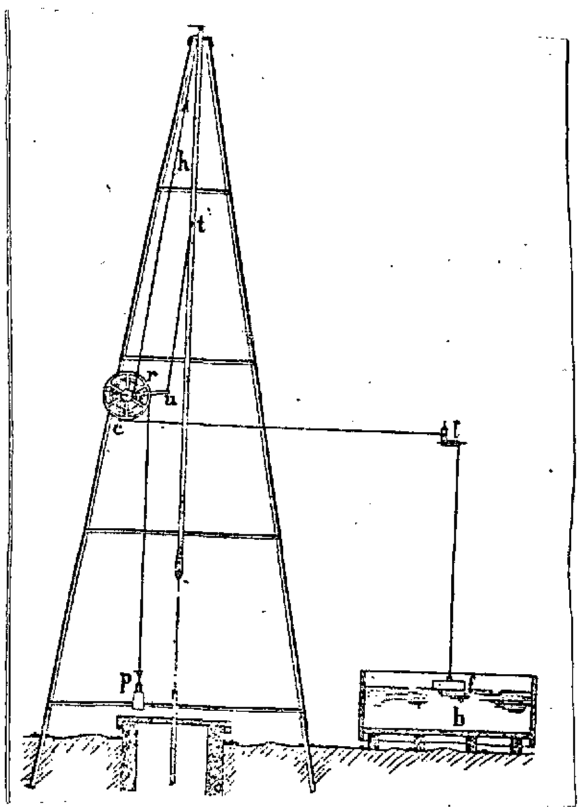
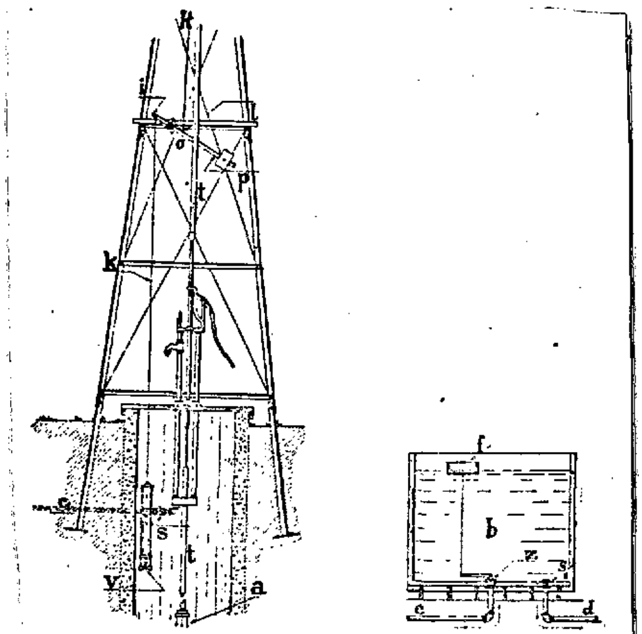


Fig. 166. Float mechanism

The cable h goes slack, the wind wheel is turned aside from the wind, the counterweight reascends and the windmill stops. When the water drops in the tank b, the float descends, the rachet c releases and the weight p tightens the cable h which faces the wheel into the wind once again.

2. Regulator with hydraulic transmission. The regulator described above is easy to install when the water tank b is a small distance from the windmill. However, when the two are separated by a large distance, it is preferable to use the regulator with hydraulic transmission shown in Figs. 167 and 168. The delivery pipe of the pump c (Fig. 167) ends in a water inlet pipe c leading into the tank b (Fig. 168), which is closed by a clack-valve z when the water reaches the top and raises the float f. The pipe d screwed into the assembly at s, at the bottom of the tank b, is the outlet pipe for the water supply.



Figs. 167 and 168. Hydraulic regulator
manufactured by Goold Shapley and Muir.

On the delivery pipe c close to the pump there is a valve V controlled by a piston activated by the water pressure. This /218
valve is kept open by a counterweight p with adjustable lever and a cable k.

When this valve is in open position, the weight p pulls on a cable h which keeps the wind wheel facing into the wind.

If the float f closes the water inlet to the tank b, the pressures increases in the delivery conduit, the piston of the valve B pulls on the cable R, which draws up the counterweight p and slackens the cable h, and the wind wheel is turned aside from the wind.

At s (Fig. 167) there is an automatic safety valve to prevent any excess pressure in the piping c.

Chapter 11

THE PRODUCTION OF ELECTRICITY BY WIND MOTORS

An installation used for this purpose will include: /219

1. A generator, which may be placed at the top of the pylon and driven directly by the shaft of the wind wheel by multiplying gears, or may be placed on the ground and driven by a rotating vertical shaft and gearbox on the ground (see Chapter 10, "Transmission Systems").

2. A storage battery operating in parallel with the generator, whose capacity in ampere-hours is 5-10 times the normal amperage of the generator.

3. A circuit breaker which connects the generator with the battery when its speed indicates a higher voltage than that of the battery, and breaks this circuit when the speed of the generator produces a voltage below that of the battery.

4. A regulating device affecting the excitation of the generator by the addition or withdrawal of auxiliary resistors on the inductive circuit. This device is absolutely necessary, since the rotation of wind wheel is extremely irregular at times, and if one were to plot a curve for the current produced it would show a number of peaks.

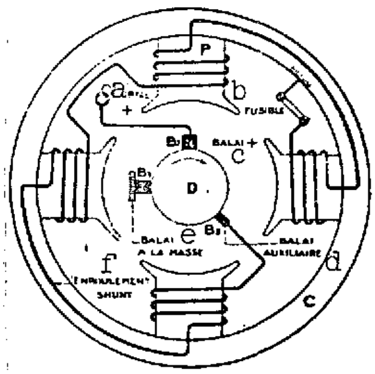
Later on we will describe the regulators manufactured by the Société pour l'Eclairage des Véhicules sur rails [Railway Vehicle Lighting Company] and the Compagnie Électro-Mécanique.

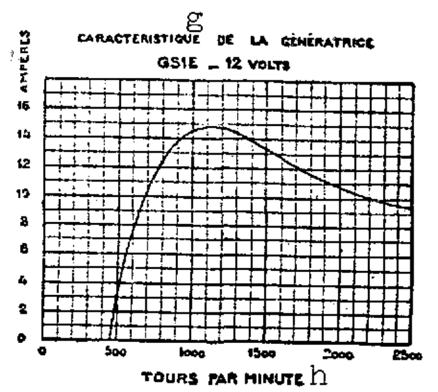
5. The usual safety and monitoring devices: voltmeters, ammeters, lead-fuse circuit breakers, switches and an electric meter (optional). The following discussion will give the recommendations of various designers and the tables which they have prepared to obviate the need for complex calculations by the installers.

Generator

An ordinary shunt generator or compound generator may be used with the wind motor, provided that the former are equipped with an excitation regulating device, types of which will be described later on. Excellent results, such as regularity of battery charge, will then be obtained.

Also used are self-regulating generators designed on the same principles as the generators used to charge automobile batteries. In the case of the American type of wind motor, with a multi-bladed wheel, operating under wind speeds of 4-10 m/sec and turning aside from the wind when this speed increases, the speed variations of the generator are much smaller than in an automobile, where the engine operates at between 300 and 3,000 rpm.





Figs. 169 and 170. The Paris-Rhône generator

Key:
- a. + terminal
- b. Fuse
- c. + brush
- d. Auxiliary brush
- e. Grounded brush
- f. Shunt winding
- g. Characteristics of GS1E 12 v generator
- h. Rpm

Thus, it has been possible to attain satisfactory results with self-regulating generators.

Fig. 169 gives a schematic diagram of the Paris-Rhône generator. This is a shunt generator with self-regulation by distortion of the magnetic field by means of an auxiliary excitation brush.

It consists of a magnetic yoke C with induction poles P around which a fine-wire excitation circuit is wound.

An armature D supports a coil whose conductors are welded to the plates of the collector, on which are mounted two brushes B^1 and B^2 which collect the current induced in the coil. The auxiliary brush at which the excitation circuit begins is at B^3. This brush can be lagged to adjust the operating conditions.

Automatic regulation is obtained by means of an auxiliary brush B3, which powers the excitation winding, which in turn affects the magnetic field.

Fig. 170 shows the curve of the current produced by the generator at various speeds. /220

Determination of the capacity of the storage battery

The capacity of the storage battery should be adequate to ensure a large enough supply of electricity to meet the needs of the installation for three or four days during a calm.

The number of horsepower necessary may be determined by the formula:

Number of horsepower = 0.0012 x number of lamps x number of candlepower per lamp.

If all the lamps do not have the same candlepower, the following formula is used:

Number of horsepower = 0.0012 x number of candlepower used simultaneously.

All the lamps powered by a given installation are not on at the same time; generally, only one third to one half of the lamps will be on at once.

The number of ampere-hours of the battery may be determined by the following formula:

$$\text{Amp-hour} = \frac{15 \times \text{number of lamps illuminated} \times \text{candlepower/lamp}}{\text{Voltage of current for lamps}}$$

or

$$\text{amp-hour} = \frac{15 \times \text{number of candlepower used simultaneously}}{\text{Voltage of current for lamps}}$$

Example: an installation has 150 lamps of 25 candlepower; 50 of these lamps are assumed to be on five hours per day, and the voltage of the current is 110 V:

1. hp = 0.0012 x 50 x 25 = 1.5 hp

2. Diameter of the wind wheel, after Table E: 5 meters. This diameter is determined for the minimum usable wind speed, that is, 4-5 m/sec according to Table E below.

3. Output of generator: 110-160 V = 2.5 kW.

4. Output of storage battery: 60 cells generating 110-125 V.

$$\text{ampere-hours} = \frac{15 \times 50 \times 25}{110} = 170 \text{ ampere-hours}$$

(after G. R. Herzog, Dresden)

Sächsische Stahl-windmotoren-Fabrik, G. R. Herzog, Dresden

TABLE E. PRODUCTION OF ELECTRICITY

Diameter of wheel in m	Output in hp under a wind speed of:			Output of generator	Storage battery in ampere hours
	4.5 m/sec	6.7 m/sec	8 m/sec		
4	1	2,33	3,5	1.5 kW.	73
5	1.67	3.75	5.50	2.5 —	73
6	2.33	5.25	8	3 —	109
7	3	7	11	4.5 —	145
8	4	9	15	6 —	181
9	5.25	11	19	6 —	218
10	6.25	13	21	9 —	290
11	7.50	16	24	9 —	290
12	9	20	26	12.5 —	363
13.5	12	25	39	17 —	435
15	15	32	45	21 —	508

The Vereinigte Windturbinen-Werke of Dresden recommends the following relationships between the diameter of the wind wheel and the generator output for voltages of 65, 110 and 220 V:

Wheel diameter	Generator output
4 and 4.5 m	1.5 kW
5 to 6 m	3 kW
6.5 to 7.5 m	4.5 kW
8 to 9 m	6 kW
10 to 11 m	9 kW
12 m	12.5 kW
13.5 m	17 kW
15 m	21 kW

This company uses an automatic battery-controlled circuit breaker. A photograph of this device is given in Fig. 171, and /223
the diagram in Fig. 171a shows its connections to the battery and the generator (Liebe system assembly).

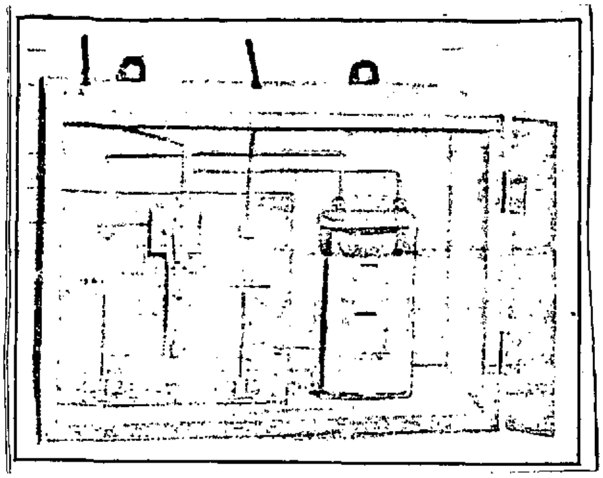


Fig. 171. Liebe circuit breaker

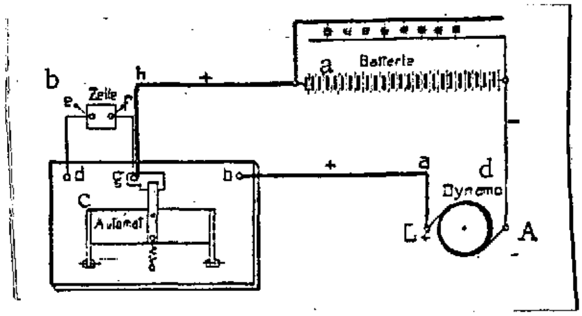


Fig. 171a. Connections of the Liebe circuit breaker

Key: a. Battery
b. Cell
c. Automatic unit
d. Generator

EFFICIENCY IN HORSEPOWER (hp) AND IN KILOWATTS (kW) /224

Wheel diameter in m		Wind speed in m/sec					
		4	5	6	7	8	9
5,5	hp	0,7	1,4	2,4	3,85	5,7	8,1
	kW	0,36	0,73	1,25	2,0	2,96	4,23
6,5	hp	1,0	2,0	3,4	5,35	8,0	11,4
	kW	0,52	1,04	1,76	8,0	4,2	6,0
7,5	hp	1,33	2,6	4,5	7,15	10,6	15,1
	kW	0,69	1,35	2,4	3,7	5,5	7,8
8,5	hp	1,7	3,33	5,75	9,10	13,6	19,4
	kW	0,88	1,7	3,0	4,75	7,1	10,1
10	hp	2,36	4,64	8,0	12,7	19,0	27,0
	kW	1,22	2,4	4,15	6,6	9,9	14,1
12	hp	3,4	6,7	11,5	18,3	27,3	39,0
	kW	1,76	3,5	6,0	9,7	14,1	20,0
15	hp	5,34	10,5	18,0	28,6	42,6	60,0
	kW	2,8	5,5	9,4	15,0	22,0	31,4

[All commas in this table should be read as periods. -- Trans.]

Wheel diameter in m	Generator output in kW	Battery output in amp-h at 32 V	Average no. of 25-candle power lamps lighted			Output in hp of an electric motor which could be powered		
			a	b	c	a	b	c
2,45	0,65	48amp-h	6	12	24	0,15	0,3	0,65
3,05	1	72amp-h	10	20	40	0,25	0,5	1
3,65	1,5	108amp-h	15	30	60	0,35	0,75	1,5
4,25	2	144amp-h	20	40	80	0,5	1	2
5,20	3	216amp-h	30	60	120	0,75	1,5	3

Columns a correspond to low-speed, irregular winds, b to average wind speeds and c to extremely high winds.

The output of the batteries is assumed to be one fourth their total capacity in amperes-hour.

The voltage of 32 V applies to extremely small installations; for larger ones, the voltage will be 65, 110 or 220 V.

Circuit breakers

Fig. 172 shows the basic structure of one of these devices: an electromagnet a supports a thin-wire coil 1 which is constantly traversed by the current from the generator and a second coil 2, with only a few turns, to which the charge current for the battery passes when the mercury switch (or another system) g is closed.

When the generator reaches a sufficient speed to produce a suitable voltage for charging the battery, the electromagnet attracts the soft iron vane ℓ with an articulation at f and regulated by a return spring r.

At this point the contact g closes, circuit 2 charges the battery, and its winding on the coils of the electromagnet increases the attraction of the vane ℓ.

When the voltage of the battery b becomes higher than that of the generator, the current changes direction in circuit 2, which places the two windings of the electromagnet a in opposition. The vane ℓ, which is no longer attracted, is returned to position by the spring r and breaks the contact g.

A spark arrester k, with a resistor r, serves to decrease or eliminate the current-interrupting spark at the switch.

CHARACTERISTICS FOR THE CONVERSION OF WIND INTO ELECTRICITY, AFTER FRIEDRICH KÖSTER OF HEIDE VON HOLSTEIN

Number of 25-candle power lamps illuminated	Output of motor which can be powered by stor. batt. for 10 h: hp	Storage battery			Generator			Diam. of Adler wind wheel in m	Production of wind turbine in kWh	
		No. of cells	Ampere hours	kWh	Volts	Amperes	kWh		per day	per year
15	0,4 hp	55	36	4	110-150	7	1,0	4,5	5 - 6	1,500 - 1,800
35	0,8 hp	55	73	8	110-150	18	2.7	5.5	7 - 10	2,100 - 3,000
60	1,25 hp	55	109	12	110-150	27	4 0	6 5	10 - 14	3,000 - 4,200
80	1,50 hp	55	145	16	110-150	36	5.4	6.5	10 - 14	3,000 - 4,200
120	2 hp	55	181	20	110-150	45	6,7	7.5	14 - 18	4,200 - 5,400
150	2.5 hp	55	218	24	110-150	60	9.0	8.5	18 - 24	5,400 - 7,200
150	2,5 hp	110	109	24	220-300	30	9 0	8.5	18 - 24	5,400 - 7,200
200	3,5 hp	55	290	32	110-150	60	9.0	8.5	18 - 24	5,400 - 7,200
200	3.5 hp	1 0	145	32	220-300	30	9.0	8.5	18 - 24	5,400 - 7,200
250	4,5 hp	55	363	40	110-150	80	12	10	25 - 33	7,500 -10,000
250	4.5 hp	110	181	40	220-300	40	12	10	25 - 33	7,500 -10,000
300	5.5 hp	55	435	48	110-150	100	15	10	25 - 33	7,500 -10,000
300	5,5 hp	110	218	48	220-300	50	15	10	25 - 33	7,500 -10,000
400	7 5 hp	110	290	64	220-300	60	18	12	33 - 48	10,000 -15,000
600	9 hp	110	363	80	220-300	75	23	12	33 - 48	10,000 -15,000

TABLE PREPARED BY THE ÉTABLISSEMENTS CHÊNE OF SAINT-QUENTIN GIVING THE CHARACTERISTICS OF GENERATORS AND STORAGE BATTERIES FOR THE PRODUCTION OF ELECTRICITY BY THE "HERCULES" WIND MOTORS WITH ROTATING VERTICAL SHAFT TRANSMISSION /227

Maximum number of 25-candlepower lamps illuminated at one time for 4h/day		4	7	9	12	16	22	30	40
Diameter of drive wheel in m		3,50	4	4,50	5	5,50	6	6,50	7
Maximum output of generator in W		350	500	800	1,000	1,200	2,000	2,500	2,800
Characteristics of battery	Number of calls	14	14	14	30	30	60	60	60
	Capacity in amperes-h	73	145	181	109	145	109	145	181
Power available on shaft of drive wheel	4-5 m/sec wind	0,35	0,60	0,75	1,00	1,25	1,50	1,75	2,00
	6-7 m/sec wind	1,20	1,60	2,00	2,50	3,00	4,00	4,50	5,00
	8 m/sec wind	1,80	2,40	3,00	4,00	5,00	6,00	7,00	8,00

The figures in this table apply to a wind motor operating approximately seven hours a day at an average wind speed of 5 m/sec.

TABLE OF OUTPUTS OF ADLER THICK-BLADED WIND MOTORS

Experience with light power plants has shown that only about one third of the lamps in the system will be on at the same time for four to five hours per day. The following figures are based on 25-candlepower, 30 W lamps.

Diameter of windmill	Output of generator	Total number of lamps in network	Number of lamps on simultaneously each day
3.05 m	500 W	50/60	15 to 20
3.65 m	900 —	80/90	25 to 35
4.25 m	1,200 —	120	Approx. 40
4.90 m	2,000 —	160	Approx. 60

A schematic diagram of a circuit breaker designed by Professor La Cour is given in Fig. 173, after a sketch by Commander Riet: mn is a horseshoe magnet able to rotate on a shaft l and whose poles n may be drawn, either to the right by electromagnet e_2 or to the left by electromagnet e_1. k_1k_2

is a horizontal copper rod with iron tips at its ends; one of these tips, k_1, constantly dips into the bucket g_1 and the other, k_2, dips into bucket g_2 only when the pole n of the magnet is drawn to side e_1.

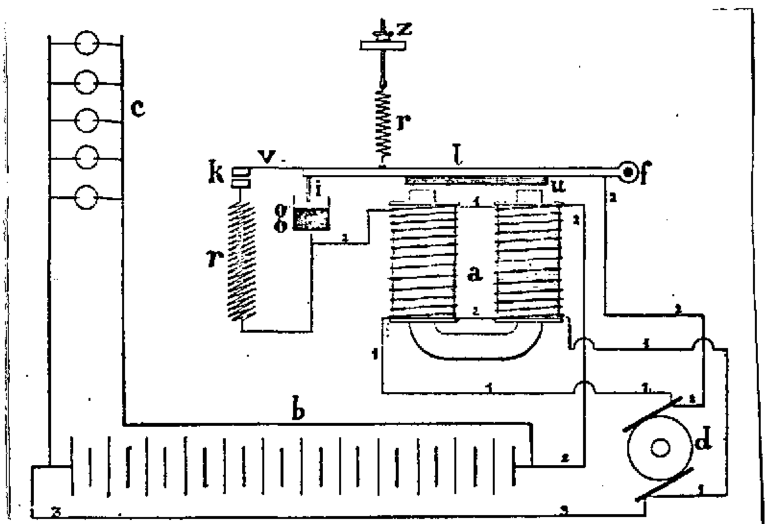


Fig. 172. Diagram of an automatic circuit breaker

The current travels at all times from a to b, the terminals of the device, through the fine wire coil ss, and, when tip k_2 dips into bucket g_2, the current is transmitted to the storage battery through the heavy wire coil zz. This occurs only when the voltage of the current from the generator is greater than that of the storage battery.

Polarized circuit breaker

Shown in Fig. 174, this device contains a solenoid whose core E has an armature with two branches BB shifting between the poles of two permanent magnets A, A.

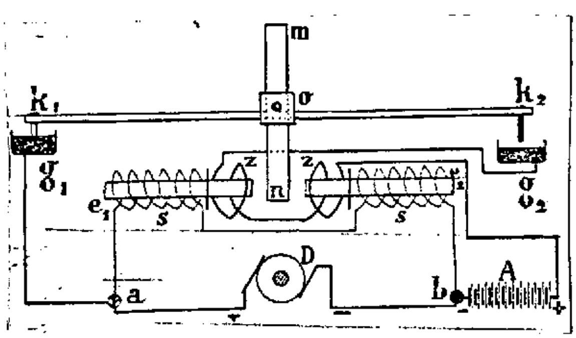


Fig. 173. Diagram of the circuit breaker designed by Professor La Cour

The solenoid has two coils: one of fine wire, D, whose circuit includes the storage battery and the generator armature, and the other of heavy wire, C, which is placed in series connection between the g generator and the battery when the circuit breaker is closed at H'. When the generator is stopped, the current from the battery is transmitted to the fine wire coil D at a rate of a few hundredths of an amp; the effect of coil D is to keep the circuit breaker open at H', in the position indicated in the diagram. As soon as the generator starts up and begins to furnish power of a few volts, its current is in inverse proportion to the current entering coil D, where the voltage begins to decrease and finally is cancelled. The lever F tilts and produces contact at H' between the generator and the battery;

but the current from the generator, which is beginning to charge the battery, is transmitted to the heavy wire coil C, which has the effect of maintaining the lever F in the position at which contact H' remains closed. /230

If the generator slows down and its voltage drops below that of the battery, the direction of the current changes in coil C and lever F tilts to the rear and cuts off the current at H', which returns the circuit breaker to its initial state.

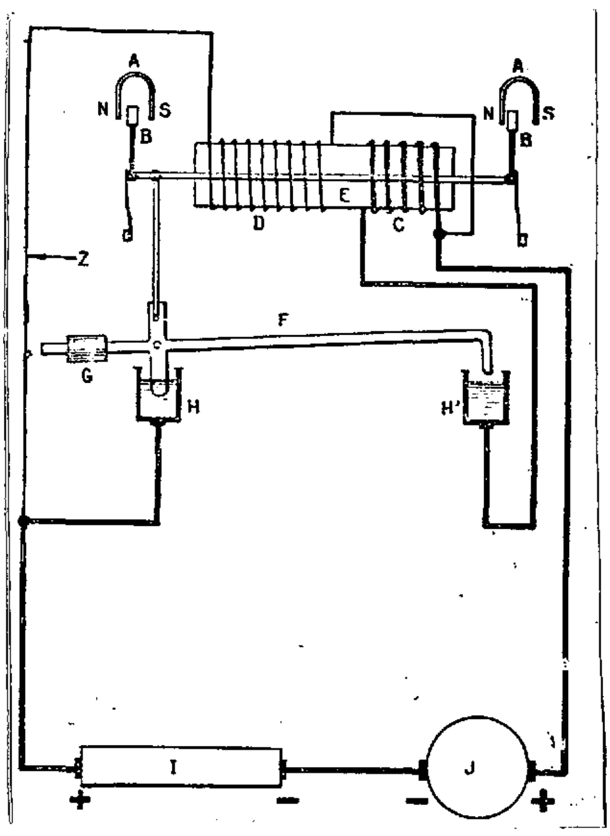


Fig. 174. Polarized circuit breaker operating under a variable voltage ranging from 25 to 110 V.

Key:
A. Magnet
B. Armature
C. Series winding
D. Shunt winding
E. Core
F. Contact lever
G. Weight for adjustment
HH'. Mercury-filled contact buckets
I. Battery
J. Generator
Z. Automatic switch

The considerable advantage of this device is that it does not consume current during operation and that it operates independently of the voltage of the battery or the generator within extremely broad limits, 24-110 V, for example. It /231 is highly sensitive and completely satisfactory for wind motors. Its disadvantage is that it consumes current when the generator is stopped, due to the fine wire coil D. This defect may be prevented, however, by placing an automatic switch at Z with branches connected to the poles of the generator, which will allow current to pass through coil D only when the generator starts up.

Shunt generator regulators

— The regulator produced by the Compagnie Electro-Mécanique (Report by G. Lacroix, Engineer, Compagnie Electro-Mécanique).

This automatic regulator is shown in Fig. 175, and its mode of branching in Fig. 175a. This device serves a three-fold purpose:

1. It automatically regulates the excitation of the generator as a function of the power supplied.

2. It allows the battery to be charged under optimum conditions for maintenance of the battery.

3. It protects the installation against certain false trips.

1. Automatic regulation of excitation

The purpose of automatic regulation of the excitation is not to keep the voltage of the generator constant for any given speed of the wind motor. Regulation of this type would be illusory in the case of parallel operation of the generator with a storage battery, since the voltage at the battery terminal ranges from 1.8-2.5 V per cell, depending on the charge state.

The voltage is kept virtually constant due to the fact that the generator operates in parallel with the storage battery in all cases. (There is no provision for operation at constant voltage without a battery; moreover, this is impossible with the device described.)

Regulation of the excitation, as performed by the device, is actually regulation of the power supplied by the generator as a function of its rotation speed. We know that the power supplied by a windmill operating at its maximum efficiency varies as the third power of its rotation speed. It would therefore be an advantage to have the generator also produce power proportional to the third power of its rotation speed, without taking efficiency into account. Now, if the excitation were kept constant, the power supplied to the generator and transmitted to the battery would increase much faster than the third power of the rotation speed.

To obtain the correct variation in power, it is therefore necessary to decrease the excitation as the speed increases, /232
or to decrease the excitation as the power increases, which amounts to the same thing.

For this purpose (Fig. 175a), the inductors i of the generator are connected directly to the negative pole on the one hand and to the positive pole on the other through an automatic rheostat connected to the terminals B and E of the regulator. The different sections of this rheostat end in contact studs g arranged in an arc of a circle on the plate of the regulator (Fig. 175). A given number of these studs are short-circuited by an elastic strip e of one piece with a ring c able to move in a vertical direction.

The vertical motions of the ring c are controlled by a drive system composed of two adjustable cores a and a'

attracted by the coils M and M'. The two cores are connected /233
by joints such that when core a, for example, is thrust into coil M, core a' leaves coil M'. An opposing spring r tends to draw the ring c and the core a' downward, with the result that the elastic strip e completely short-circuits the automatic rheostat when the device is off.

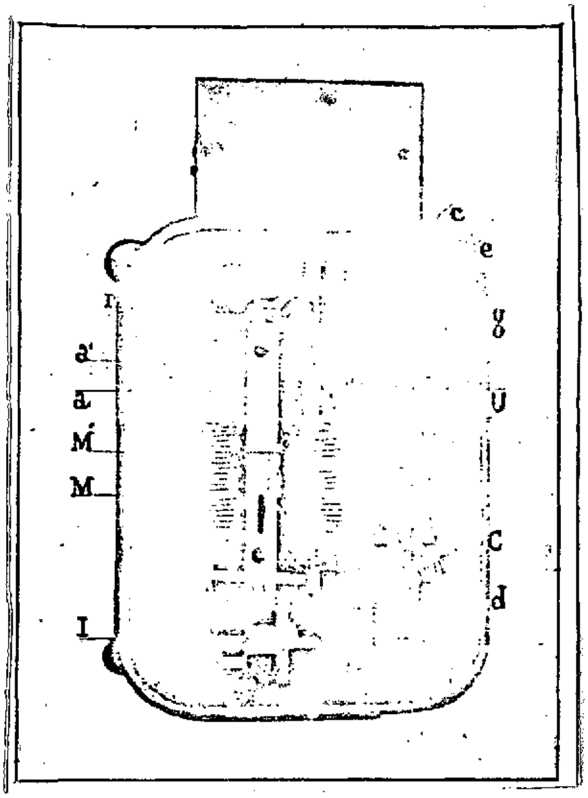


Fig. 175. Automatic regulator produced by the Compagnie Électro-Mécanique

The two coils M and M' consist of voltage and current windings arranged in such a way that the sum of the attractive forces on the two cores a and a' is proportional to the generator output. Under these conditions, when the output of the generator increases, the ring c rises until the opposing force of the spring r is equal to the attractive force of the coils M on the cores a.

The corresponding motion of the contact strip e brings a given number of studs g and the corresponding resistors into the circuit, thus producing a decrease in the excitation current. It is sufficient to determine the values of the resistors switched into the circuit between the different studs g once and for all to obtain the output variations of the generator as a function of speed.

An adjustable air shock absorber d works to prevent permanent oscillations in the moving parts.

2. <u>Devices ensuring a correct battery charge</u> /234

a) <u>Main switch</u>. The main switch I is a circuit breaker which connects the generator and the battery in parallel. It closes as soon as the voltage from the generator is equal to that of the battery, and it opens when there is a very slight return of current from the battery to the generator. This switch, which serves to open or close the circuit only when the current is low or zero, contains only ordinary metal contacts with the addition of a carbon spark-arresting contact.

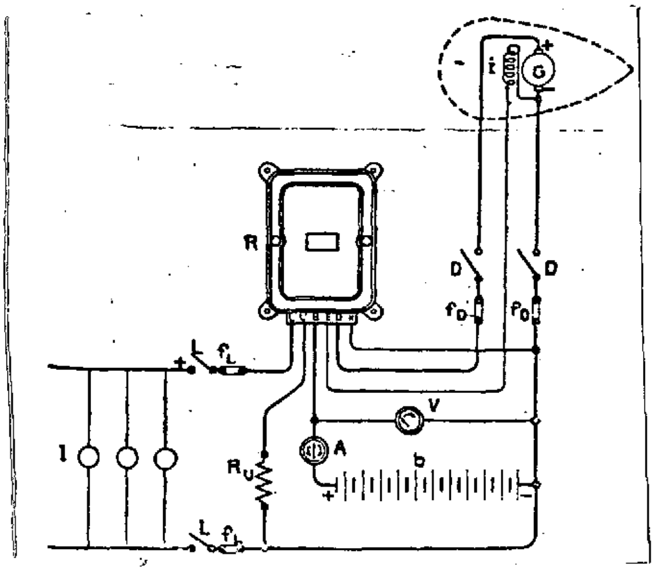


Fig. 175a. Branch diagram of regulator (Fig. 175).

Key:
- G. Generator
- i. Inductors
- R. Automatic regulator
- b. Storage battery
- 1. User circuit R_U
- R_U Ballast resistor
- D. Generator switch
- L. Light switch
- f_D. Generator fuses
- F_L. Light fuses
- V. Voltmeter
- A. Ammeter with 0 centerpoint

b) Charge limiter. The charge method which is known to be optimum for maintaining the battery is charging with increasing voltage and decreasing current intensity. Since the current intensity decreases much more than the voltage increases, the power supplied by the dynamo will decrease constantly during charging. This charging method cannot be used with a generator driven by a wind motor, whose output depends only on the wind speed. To obtain charging with decreasing current, part of the current supplied by the generator must be derived from outside the battery, for example, from a resistor R_U. A special relay U or "charge limiter" thus connects a resistor R_U in parallel with the battery when the charge current exceeds a given level which varies with the charge state, that is, with the voltage at the battery terminals. The relay U remains closed for increasing periods of time as the battery becomes more highly charged. When the battery has been completely charged, the relay remains closed and all the current from the generator is transmitted to the resistor R_U.

Since the relay U must open and close the circuit of the resistor R_U during charging, in addition to ordinary metal contacts it has a mercury contact-breaker in which the opening and closing sparks occur.

3. Safety devices

a) Discharge limiter

The discharge limiter C prevents excessive discharge from the battery. It consists of a minimum-voltage relay which opens when the voltage at the battery terminals reaches 1.8 V per cell (end-of-discharge voltage). Since this relay is placed inside the plumbable cover of the assembly, it cannot be closed by hand once it has been opened, which gives complete assurance that the battery will not run down. It closes automatically at the same time as the switch I when the battery has been recharged, and it remains closed as long as the battery voltage is higher than 1.8 V per cell. /235

b) Voltage limiter

When the charge circuit of the battery is interrupted for any given accidental cause, the speed of the wind motor increases while the ring c drops, short-circuiting the excitation resistor. For these two reasons, the voltage of the generator increases in considerable proportions (3 to 4 times the normal voltage). The coils and resistors of the regulator, which are set for normal voltage, would quickly be put out of operation if a "voltage limiter" relay positioned inside the regulator under the plate were not available to short-circuit the inductors i and thus quickly cancel the generator voltage. The operation of the relay at the same time opens the relay C, thus triggering a break in the current which warns that the system is malfunctioning. Once relay T has operated, it remains blocked by a mechanical lock. Normal operation can be resumed only after the cause of the malfunction has been discovered and the relay has been unlocked by hand by means of a special knob on the lower part of the regulator.

Regulator of the Société d'éclairage des Véhicules sur Rails (E.V.R.) [Railway Vehicle Lighting Company].

This device, shown in Fig. 176, includes: 1) a highly sensitive circuit breaker d, with a fine wire coil (connected in parallel with the generator) and a heavy wire coil (connected in series to the battery charge circuit); 2) the emergency circuit breaker c; 3) an automatic rheostat regulating the excitation or the inductor coil of the generator.

This regulating rheostat consists of a solenoid coil s containing a moveable iron core. An extension n of this core plunges into a mercury-filled cylinder whose diameter is slightly greater than that of the core n.

This cylinder consists of a given number of iron washers separated by insulating washers, each of the iron washers being connected to one of the turns of the rheostat e.

The inductive current enters through the bottom of a mercury cylinder and leaves through the upper end of the rheostat e. When the iron core of the solenoid descends into its cylinder, the level of the mercury rises and makes contact with the upper washers forming the walls of the cylinder. As a result, an increasing number of turns of the rheostat e are disconnected as the iron core is thrust farther into the mercury cylinder. /236

At r there are additional resistors for the coil of the solenoid s allowing it to be adapted to various voltage levels for the generator current.

This device makes it possible to regulate the output of the generator without inordinate variations in its voltage. This type of regulator, which for some time been built for the lighting generators driven by the wheels of railway cars, has been specially adapted to wind motor generators.

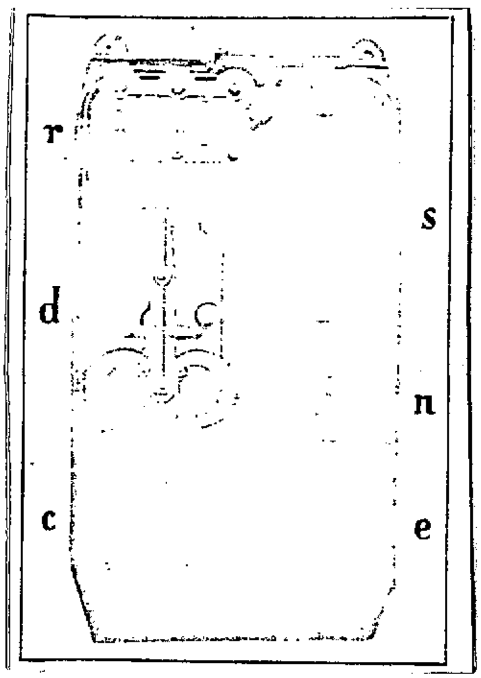


Fig. 176. The regulator of the E.V.R. Company

Regulation by a clutch or friction-coupling

The Adler, F. Köster Company of Heide, Holstein, has patented a friction-coupling of the gradual clutch type which can be used to regulate the drive power in such a way that a sliding effect is produced when the speed of the wind wheel exceeds a given maximum. A possible criticism of this system is the heating of its parts and the inevitable wear and tear on the friction surfaces, but special construction and compensatory devices will eliminate or diminish these drawbacks.

Regulation by variable-tension belt /237

To regulate the action of the wind wheel on the generator, Professor La Cour has invented a pulley with lever, schematically shown in Fig. 177, after a sketch by Commander Riet. If there is an excessive increase in the wind speed, the return pulleys c being mounted on a lever db, the vertical belt vv' slides over the pulley c. The adjusting weight l and the weight of the pulleys c place the belt vv' under a given tension; when the pull of the tight side v' attains the level of this tension, the belt slides and the power transmitted no longer increases.

One disadvantage of this procedure appears to be considerable fatigue for the belt vv' due to the friction to which it is subjected by the pulleys.

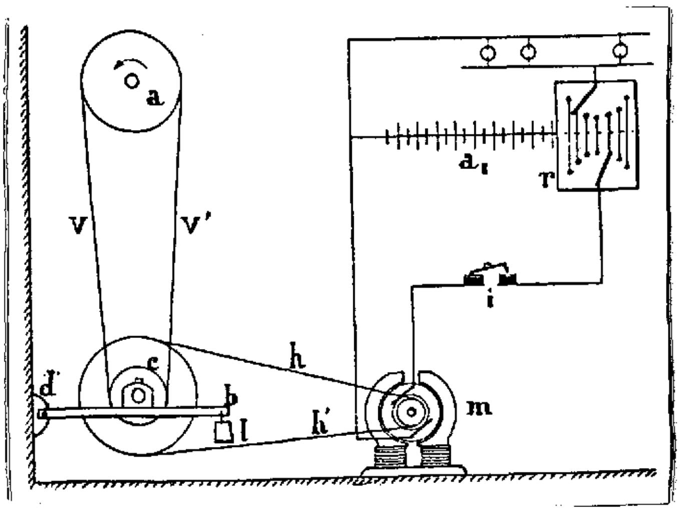


Fig. 177. Regulation by variable-tension belt

Key:
- a. Wind wheel
- vv'. Vertical belt
- c. Return pulley
- db. Lever articulated at fixed point d
- l. Counterweight adjusting the tension of the belt
- hh. Horizontal belt
- m. Generator
- i. Circuit breaker
- a_1. Storage battery
- r. Charge and discharge reducer

Regulation by gravity

Commander Riet has drawn attention to a method of accumulating work designed by the German engineer Max Gehre. This consists in using a windmill to raise a suitably calcu-alted weight, which is then allowed to drop slowly; this system ensures the regular operation of the generator producing the electric light necessary for the Busum lighthouse in Holstein.

The energy from a wind motor may also be used to elevate water or fine dry sand which is then poured /238
over a bucket wheel (or water turbine) which drives the generator.

Description of the 1500-2000 W wind generator of the Compagnie Electro-Mécanique (Report by G. Lacroix, Engineer, Compagnie Électro-Mécanique).

This 1500 W wind generator has been designed to meet the most frequent needs of small-scale agriculture. It is able to start under a wind speed as low as 2-2.5 m/sec, operates at full capacity at 5-6 m/sec and continues to rotate even under storm winds of more than 12 m/sec. Since the average annual wind speed in France is approximately 5 m/sec, this generator can be used successfully in all areas. It operates completely automatically and requires no monitoring. Maintenance merely consists of lubrication once a year. An automatic centrifugal-force brake completely prevents any accidental overspeed of the windmill, which thus is able to operate without risk of any kind.

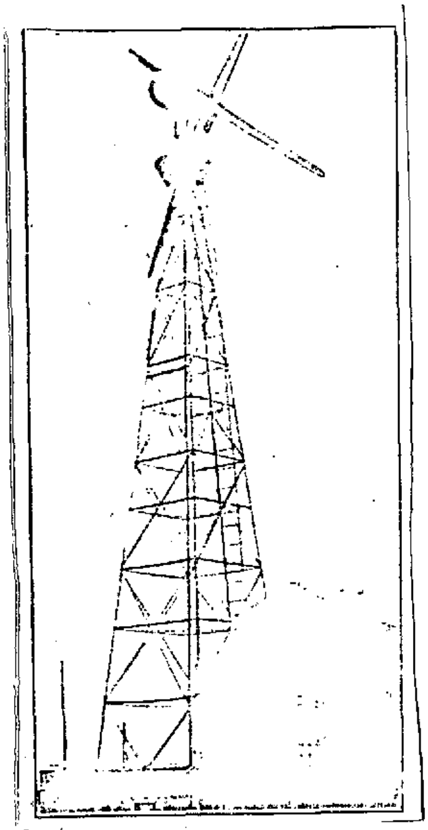


Fig. 178. The Darrieus wind generator

The blades are able to tolerate a speed of 150 rpm. Due to the small area they offer to the wind, they are able to withstand the most violent storm winds.

It is possible to obtain an output of 2 hp from the battery alone, and 3-4 hp from the wind generator operating in parallel with the battery.

A 1500 W wind generator installation includes:

1. The electric generating unit per se, which consists of a wind motor with four blades 8 m in diameter, driving a generator by means of a multiplying gear train (Fig. 178).

2. The power regulating devices: an automatic excitation regulator /239 for the generator, a storage battery, and measuring and safety devices installed in a sheltered site some distance from the wind motor.

The various units, including the generator and multiplying gears, which make up the electrical generating unit are installed together in a sheet-metal casing forming a single unit and mounted on a pole or pylon.

Generator

This is an ordinary dc generator with switching poles, whose power and voltage may be determined in each specific case as a function of the average wind speed in the geographical area involved and the type of service for which the installation is designed. For example, when it is to be used merely to light a given building or area, particularly a humid building such as a stable, it could be advantageous to use a fairly low voltage of 24, 48 or 65 V. However, given the high cost of low voltage motors, it will be necessary to choose a higher voltage of at least 110 V when the installation is also intended to produce motive power. The choice of voltage has virtually no influence on the cost of the storage battery.

The following description specifically pertains to two installations, one 24 V and the other 110 V, which have been constructed.

The generator is designed to operate at full capacity beginning at 500 rpm. At this speed, however, the power supplied by the windmill is inadequate to excite the generator, even with no load (8 A at 24 V, that is, approximately 200 W). As a result, in practice the generator is used only at speeds of 700 rpm or more. The maximum speed the generator is able to tolerate is 3000 rpm.

The rated output of the generator is 1200 W, corresponding to a current of 50 A at a voltage of 24 V, or 11 A at 110 V. However, the types of generators used have a wide range of operation, and in steady-state operation between 1500 and 2000 rpm, they are able to deliver 1850 W (70 A at 25.6 V or 15 A at 125 V).

During the tests, the generator frequently tolerated peaks of more than 3 kW without without evidence of overheating. This high tolerance for overloads is of prime importance for a generator driven by a wind motor. It allows the windmill to withstand, without risk of overspeed, the brief gusts which may occur, even when the average wind speed seems to be fairly /240
low, and during which the tower supplied by the wind motor may be much higher than the rated output. This is shown by the diagram in Fig. 179, which represents the current generated by a 24 V generator for 1/4 hour on March 18. 1927, from 11:30 to 11:45 a.m. It may be noted that the average current is approximately 25 A, corresponding to half the rated load of the installation, while within a three-minute interval a succession of gusts has produced an increase in the current to 97 A, which, taking the correlative increase in voltage into account, represents power of more than twice the rated output.

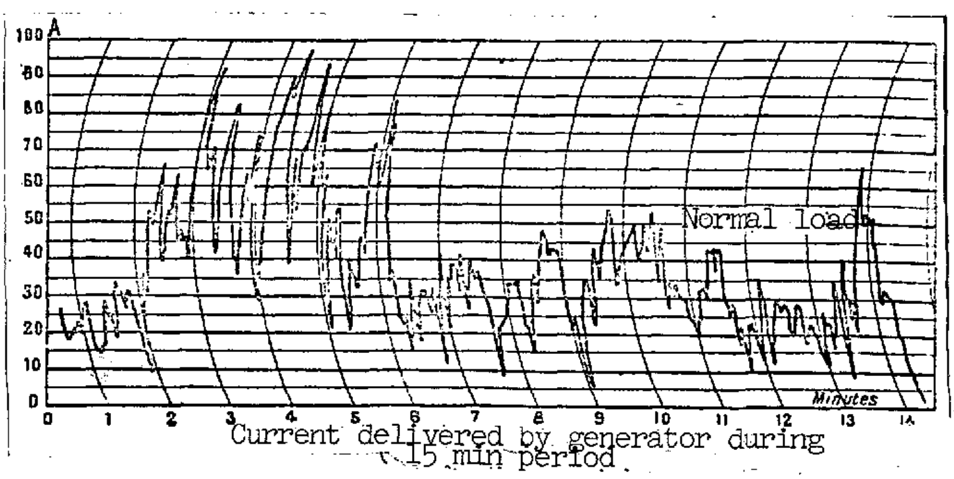


Fig. 179. Diagram of performance of wind generator (Fig. 178).

Multiplying gears

The gear train, with an intermediate shaft, consists of two sets of gears with straight spur teeth, carburized and straightened by the Maag process. In each of these sets, the wheel has 58 teeth and the pinion 13 teeth, with the result that the multiplication ratio is quite close to 20. The main shaft, at whose end the windmill blades are mounted, is in line with the secondary shaft which drives the generator through an intermediate four-pin coupling. The intermediate shaft is located to one side. All the shafts are mounted on ball bearings.

The gears and bearings are contained in a water-tight, oil-filled gearbox through which only two shafts are able to pass. The splash lubrication requires no supervision. The oil need only be changed from time to time, once a year, for example. An easily accessible oil level reveals any accidental leakage.

Wind motor

/241

The wind motor has four identical wooden blades affixed to a cast hub. Each blade is double, consisting of a large blade 4 m long which receives the initial thrust of the wind, braced by a shorter blade. The two blade elements are connected by two spacers. In this way, maximum resistance to the thrust of the wind is obtained without any necessity for the tension adjusters or brace rods which are widely used.

The underlying theory for this wind motor was given in Chapter 5. As we stated there, the fish-shaped profiles of the vanes have the advantage of automatically limiting the power supplied by the windmill at any given wind speed.

Of course, this automatic speed limitation depends on the use of a generator with appropriate characteristics and involves the assumption that there are no electrical breakdowns in this generator (break in excitation, etc). It is therefore necessary to provide an automatic safety brake capable of stopping the windmill when its speed exceeds a set value.

Automatic brake

This band brake acts on a small-diameter cast drum keyed into the secondary shaft of the multiplying gear train. It may be controlled manually from the base of the post by means of a metal cable for starting and stopping the wind generator; a centrifugal force device operates the brake automatically when the speed of the windmill exceeds a given value, which prevents overspeeds when there is a failure in the generator.

The brake is not designed for long-term operation. It should be used only to stop the windmill, and in no case should any attempt be made to use it to moderate the speed of the windmill during high winds.

Regulating assembly

The regulating assembly used by the Compagnie Électro-Mécanique for wind motor installations has been described earlier.

Battery

The characteristics of the batteries used for the Bourget tests were as follows:

A type ETP 6 24 V 12-cell battery manufactured by the Travail Électrique des Métaux (T.E.M.)[Electric Metalworking Company], with a capacity of 180 A/h and a maximum charge current of 50 A.

Type SA 9 110 V 55-cell batteries manufactured by the Fulmen Company, with a capacity of 140 A/h; rated charge current 16 A.

The capacity of the battery may be reduced to a level corresponding to the rated output of the generator (capacity in A/h equals ten times the rated current of the generator). /242

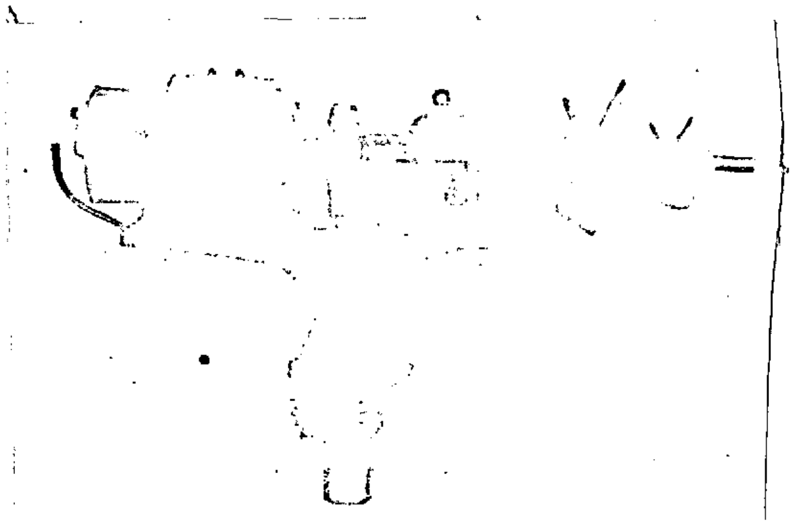


Fig. 180. Mechanism of the Darrieus wind generator

Fig. 180 is a photograph of the head of this wind motor.

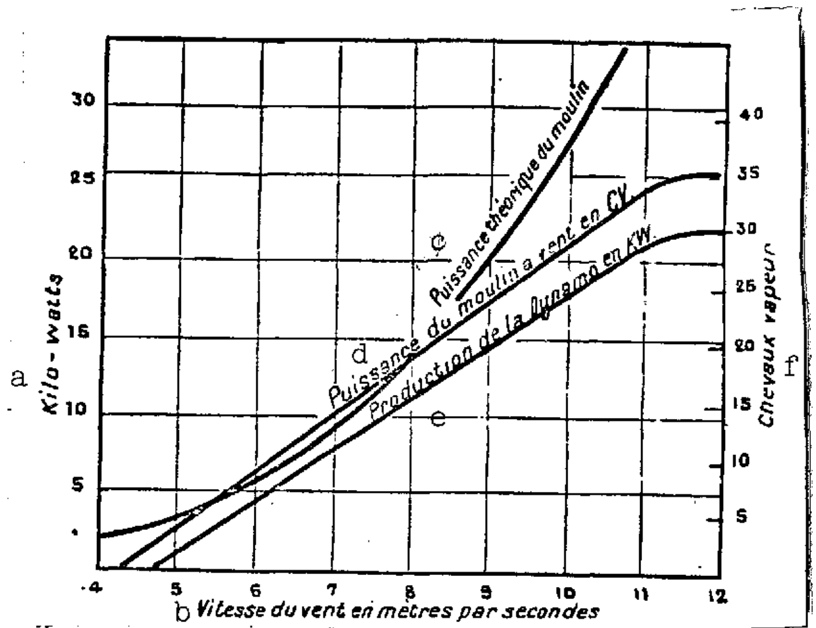


Fig. 181. Diagram of the results of measurements obtained by the Comité du gouvernement danois pour la mécanique [Danish National Committee on Mechanics] on a Mammouth windmill 16 m in diameter. The theoretical outputs in hp and in kW are constant up to a wind speed of approximately 11.40 m/sec due to the system for adjusting the surface area of the vanes.

Key:
- a. Kilowatts
- b. Wind speed in m/sec
- c. Theoretical output of windmill
- d. Output of windmill in hp
- e. Production of generator in kW
- f. Horsepower

Graphs of the performance of a vertical-shaft turbine /244

The graphs given in Fig. 182 were obtained during the day on October 12, 1929, by Mr. Lafond, a Montpellier constructor whose assemblies were described in Chapter 7 on "Pananemones." The installation consists of:

1. A Lafond wind turbine with a diameter of 3 m and a height of 3 m, mounted on:

2. A metal pylon raising the turbine 4.50 m above ground level;

CAPACITY OF WIND GENERATORS /242

Output in W	Voltage	Lights on at the same time 4 to 5 h per day	Use
300	24		
600	24-32-55-110	12	Electric boiler, sharpening of iron
600	32-55-110		
600	32-55-110	25	1/2 hp motor, boiler, sharpening of iron, etc
1,500	110	36	1 hp motor and small electrical appliances
2,500	110	60	2 hp motor
4,500	110	100	3 hp motor
		200	5 hp motor

(After the Cyclone Company,
Compiègne

ANNUAL COST PRICE OF ELECTRICITY SUPPLIED BY GASOLINE ENGINE, /243
THE PUBLIC POWER NETWORK AND A ONE kW "CYCLONE" WIND MOTOR
OPERATING SIX HOURS A DAY

	Gasoline engine	per day	per year	"Cyclone" wind motor	per year
Gasoline	2 hp engines 1 ℓ gasoline. for 6 h: 6 ℓ at 1.80 F/ℓ	10.80	3,888	15 ℓ oil at 4 F/ℓ	60
Lubrication:	1/2 ℓ oil at 4 F/ℓ	2.00	720	4 kg grease at 6 F/kg	24
Labor:	1 h at 2 F/h	2.00	720	20 h at 2 F/h	40

[Table continued on next page]

[Table continued]

	Gasoline engine per day	Gasoline engine per year	"Cyclone wind motor"	per year
Maintenance:		220		190
Total per year		5,548	Total per year	314

Annual cost price of electricity supplied by the public power network:

6 kW x 360 = 2,160 kW at 1.70 F = 3,672 F.

3. A 30 V, variable speed dc generator, completely screened and directly connected to the main shaft of the turbine;

4. A 30 V, 100 A/h cadmium-nickel storage battery.

This type of storage battery, which remains completely charged in an open circuit, does not sulphate, is able to tolerate extremely variable charges and discharges and requires virtually no maintenance.

5. A circuit breaker and a complete panel including switches, an ammeter, a voltmeter, a counter, etc.

An installation of this type is able to power 8 20 W lamps for three hours a day, for example. This represents the normal lighting for a plant, farm, villa, country-house, etc., with 15-20 lamps installed, but not lighted all the time. Its cost is approximately 32,000 F, loaded and ready for shipping from the plant. /245

Examples of wind generator installations (extracts from a conference with Commander Riet)

A) The La Cour installation in Askov (1903).

This generator powered 450 incandescent lamps, two arc lamps and two electric motors. The balance sheet was as follows:

a) Purchase price and installation costs (including property, structures and backup motor) 16,000 crowns

b) Utilization costs per year 564 crowns

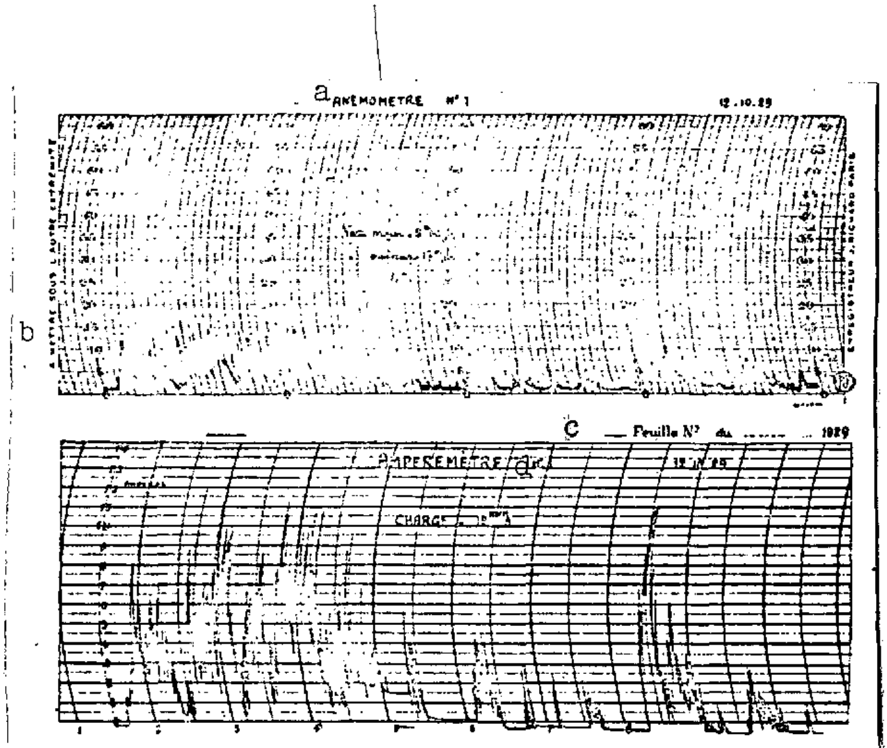


Fig. 182. Lafond turbine: graph of variations in wind speed during the day on 10/12/29. Graph of variations in the corresponding charge current.

Key: a. Anemometer No. 1
b. To be placed under other end
c. Sheet number [blank] of [blank], 1929
d. Ammeter

c) Annual revenue, 5,000 kWh at 1-1/2 crowns/kWh 2,500 crowns
d) Net profit: 2,500-564 = 1,936 crowns, that is approximately 12% of the invested capital.

N.B. -- The Danish crown was worth 1.50 F in 1903.

e) Cost price per kWh:

$$\frac{564}{5,000} = 0.1148 \text{ crown} = 0.1692 \text{ F.}$$

d) Sale price per kWh: 1/2 crown = 0.75 F.
f) Period of amortization of capital:

$$\frac{16,000}{1936} = 9 \text{ years (in round numbers)}$$

e) Proportion of cost involved in production of backup motor: 400 kWh, that is, $400 \times \frac{100}{5,000} = 8\%$ of the total production.

B) Installation of the manorial estate of Lindenbussch, close to Pyritz, Saxony (1912).

This assembly operated without a backup motor.

The general arrangement was as follows:

1. Driven directly by mechanical transmission: a mealer, a chaff cutter and a crusher located in the immediate proximity of the wind motor.

2. The output from the storage battery was used to power:

a) 135 metal-filament lamps lighting the chateau and the farm buildings.

b) by a 3 hp electric motor, the centrifugal wheel of a butter churn, the pump of a well and a chopping machine for animal provender.

c) by a second 4 hp electric motor, the motor of a band saw, a sculler and a lathe in the wheelwright's shop and a boring machine, a lathe and two bellows in the forge.

Here is the information given by the owner on the economic efficiency of this installation:

a) purchase price and installation costs:	25,000 marks
b) utilization costs, including interest and amortization of invested capital	2,500 marks
c) annual electrical consumption:	11,755 kWh
d) Cost price per kWh:	

$$\frac{2,500}{11,755} = 0.212\text{ M, that is, } 0.265\text{ F.}$$

Since the interest and amortization are included in the utilization costs, the amortization will be completed prior to the tenth year of service, and from that time on the supply of electricity will be virtually free. We have seen that this result was obtained in Askov after nine years.

Moreover, this decrease in cost to a virtually free supply of electricity is characteristic of all wind generator installations. Their basic advantage is economic.

The current increase in costs, which affects thermal power plants as well as this type of installation, does not diminish this advantage in any way, since wind still remains a free energy source.

Note -- the above costs are given in gold francs, the prewar currency.

Ground lighting of aircraft routes

This involves setting up a large number of wind motors, each driving a small generator which charges a storage battery, along regular commercial aircraft routes and in areas without public electrical networks.

A lighthouse or beacon is installed on a pole above the pylon and the wind wheel and a suitable clocking mechanism turns the beacon on in the evening and off in the morning.

The generator is at the end of the wind wheel shaft, with suitable gearing.

The storage battery is installed in a heat-insulated box on a platform at a given height within the pylon, which is constructed of galvanized steel angle irons. The cells of this battery contain an extremely large reserve quantity of acidulous water, the glass cell-boxes being nearly twice as high as the plates, which are provided with long connections to pass over /247 the cell-boxes. The weight of the battery contributes to the stability of the pylon.

The voltage is 12 V, there are six cells, and the diameter of the wind wheel is no more than 3 m, which is more than adequate, since the battery need only power a single lamp.

The above information was furnished by the Etablissements Cyclone, which has specially researched and developed these assemblies.

Chapter 12

SPINNERS TO POWER AIRCRAFT GENERATORS

Airplanes are equipped with a generator to power their lighting and radio systems. In large aircraft, this generator is provided with a small gasoline engine independent of the main engine, but in small and average-sized assemblies, this generator is driven by a spinner which is a small wind motor driven by the pressure of the air displaced by the aircraft. /248

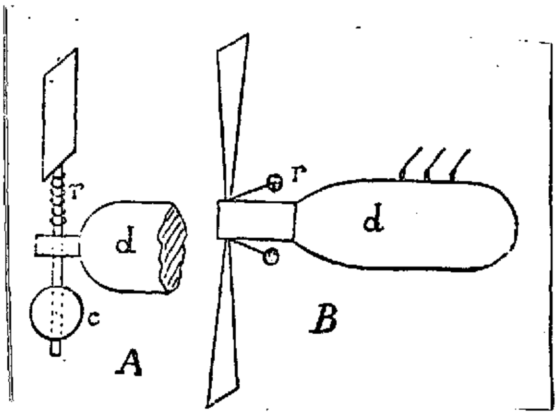


Fig. 183. Spinners and aircraft generators

There are two types of spinners. One is a single-blade airscrew (Fig. 183-a), whose angle of attack is modified, depending on the speed of the aircraft, by a balancing counterweight c which slides on a rod and acts on the pivoting blade and is returned to normal position by a spring r. The other type is a two-blade airscrew (Fig. 183-b) whose swiveling blades are controlled by a centrifugal regulator r.

Fig. 184-A shows the self-regulating device (Aéra Company) of a single-blade airscrew, C, attached to an arm B which passes through a sleeve keyed into the generator /249
shaft. At the end of this arm is a counterweight D and two other weights M attached to an oblique rod E. A spring R attached to the arm B tends to bring the rod E parallel with the shaft, that is, to draw it toward the shaft; the higher the rotation speed, the closer the rod E approaches a position perpendicular to the shaft of the generator, which increases the angle of the airscrew blade and keeps the rotation speed roughly constant and independent of the wind produced by the aircraft.

With a 40% variation in wind speed, the rotation speed varies merely by 5% and the assembly weighs only a kilogram.

Fig. 184-D shows a generator used for lighting, heating and charging storage batteries on airplanes. The output is 500-1200 W and the voltage 16 or 24 V. This is a dc assembly with voltage regulator.

The airscrews of spinners designed to power auxiliary machines such as generators, alternating generators for radio transmission, pumps, and photographic magazines have two blades whose angle with the ground is adjusted by means of index-marks

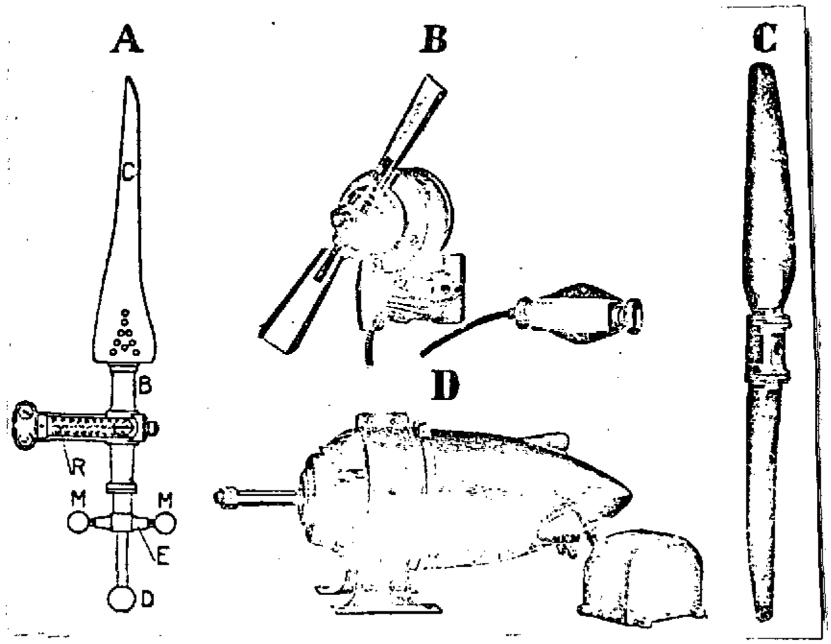


Fig. 184. Airscrews and generator manufactured by the Aéra Company

graduated in degrees on the steel hub. The blades are wood and are 0.60 m in diameter (Fig. 184-C).

At atmospheric pressure on the ground, the output of this /250 spinner is:

3.4 hp at 120 km/h
5.8 hp at 150 km/h
9 hp at 180 km/h

The output decreases with increased altitude.

To light on-board assemblies such as clinometers, compasses, map cases and angle, sideslip and stall indicators, the batteries or storage batteries may be replaced with a very small, low-voltage generator (4-5 V or 0.5 ampere) weighing only 1100 g) (Fig. 184-B), driven by a spinner with blades which can be oriented by means of a cable hand-held by the pilot (Aéra Company).

The use of spinners has the following drawbacks: the necessity of placing the generator outside the cockpit, poor mechanical efficiency and lowering of flight characteristics.

(see: Pierre Frank, <u>La T. S. F. dans l'aéronautique</u>

[Radio communication in aeronautics]; Suffrin-Hébert et Jarry, <u>Construction des avions</u> [Aircraft design]; <u>l'Equipement electrique</u> [Electrical equipment], Puteaux, Seine, and the Aéra Company, Paris.

Chapter 13

PROPULSION OF SHIPS BY WIND MOTORS

The concept of propelling ships by means of a wind wheel replacing the sails is of fairly ancient origin. In his book Initiation aux progrés récents de al Mécanique des fluides [Introduction to Recent Advances in Fluid Mechanics], [1], Darrieus mentions an invention by the Frenchman du Quet in 1714, and reproduces an old engraving (Fig. 185) which shows the propulsive assembly consisting of five trapezoidal sails mounted on the spokes of a large wooden wheel in a vertical plane. /251

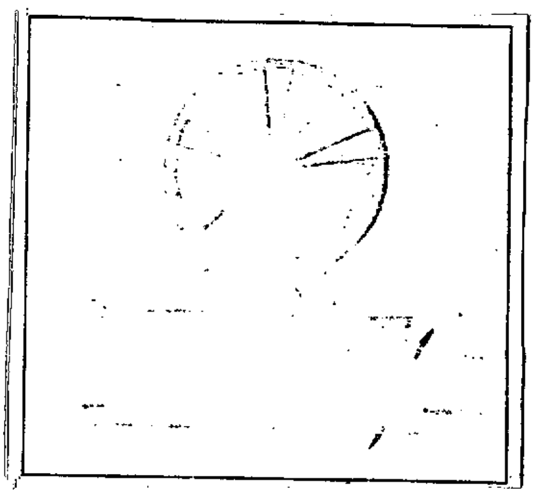


Fig. 185. The du Quet ship, 1714.

In 1923, with the aid of the Office national des Inventions [National Office of Inventions], Constantin was able to adapt a two-blade air-screw to the ship Le Bois-Rosé, shown in the photograph in Fig. 186.

This ship, which weighed close to 6 t, was equipped with a wind propeller 9 m in diameter, which, through a system of gears and a clutch, drove the ordinary ship's propeller in the water. The speed of the ship was approximately 1/3 the wind speed; under an 8 m/sec wind, the ship reached a speed of 5.70 m with a tail wind, 6 m with a head wind and 6.50 m in a cross-wind. The wind propeller oriented itself automatically. /252

Unfortunately, this remarkable test assembly foundered during towing at sea. Its propeller is stored in the Office of Inventions in Meudon. However, with this system Constantin was able to obtain a speed of 20 km/h with a mechanism which was always ready for operation, not requiring the difficult and dangerous manuevers necessary for sails, and much more solid than the latter.

It is regrettable that these tests were not resumed, since the wind motor propulsion system made it possible to sail in a straight line without having to tack before the wind.

A ship equipped with cylinders rotating on vertical shafts driven by the friction of the wind, in conformity with the theories known as the "Magnus phenomenon" (see the book by Darrieus cited above) was invented by A. Flettner. This invention does /253 not seem to have been followed up (see also Lafay, Contribution expérimentale à l'Aérodynamique due cylindre et à l'étude du phenomène de Magnus [Experiments on the Aerodynamics of Cylinders and REsearch on the Magnus Phenomenon], Dunod, 1912, 5.60 F.

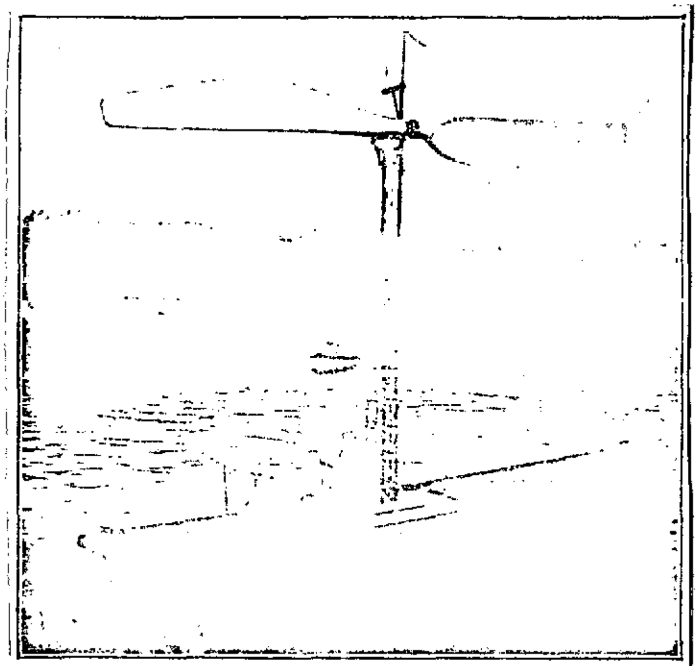


Fig. 186. The ship Le Bois Rosé, designed by Constantin.

Chapter 14

MEASUREMENT OF THE SPEED AND POWER OF WIND

In constructing a windmill, it is necessary to locate the best possible site, that is, one in which there is as much wind as possible and eddies are at a minimum. In an ideal installation, there should be no obstacles, even ones which are not as high as the wind wheel, within a 150 m radius from the pylon. /254

Eddies are caused by surrounding obstacles such as mountains, hills, large trees, houses, towers, steeples, etc. We have seen installations in which a large reinforced concrete tank had been placed quite close to the steel pylon on which the windmill was mounted, which definitely would have a detrimental effect on the efficiency.

Determination of the height at which the wind wheel should be placed is extremely important. Generally, the wheel will receive greater thrust from the wind and will have fewer eddies to contend with as its elevation increases. The following differences according to wind speed are the result of experiments performed at the Eiffel Tower in Paris by the <u>Bureau météorologique</u>:

	Average wind speed at a height of 300 m	Average wind speed at a height of 20 m	Ratio of the speeds
Hot season	7.05 m	2.24 m	3.1
Cold season	8.19 m	1.80 m	5.6

This table shows that there is always a considerable advantage in placing the wind motor on an eminence or an extremely high pylon. If this motor is designed to supply water to a tank, the best solution is obviously to construct this tank on a reinforced concrete tower and to mount the steel pylon atop the tank. /255

One should take into account the wind speed at the same time at different heights; this can be determined by means of fixed or portable recording anemometers operated over a given period of time. A few of these devices will be described below. It should be noted that the costs involved in building an extremely high pylon are quickly recovered by the increase in power of the wind motor.

Spinner-anemometer designed by Dr. Robinson

Invented about 50 years ago, this simple and durable device is thoroughly adequate for the determination of wind speeds for the construction of wind motors.

It consists of an extremely light spinner, sometimes constructed of aluminum, equipped with four hollow semi-spheres. The wind has a greater effect on the hollow face of the semi-spheres than on the curved face, with the result that the spinner always turns in the same direction without any need for orientation, provided that it is kept in a horizontal position (Fig. 187).

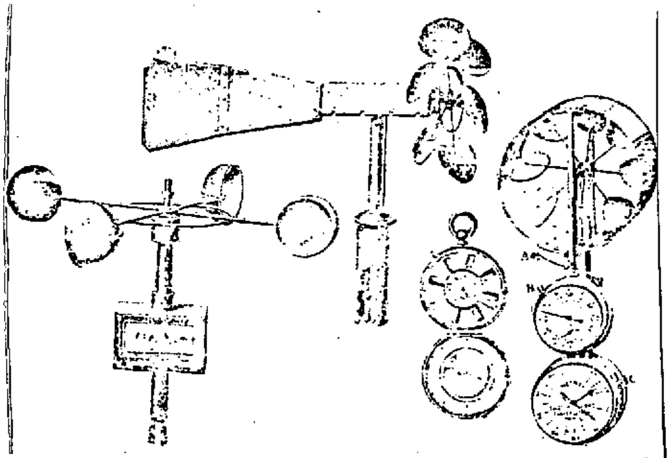


Fig. 187 to 190. Anemometers.

Its rotation speed under a given wind speed increases as its diameter decreases. A model designed by the Jules Richard Company performs four turns per meter of wind speed; it is equipped with a rotation counter and a second chronometer. /256

To facilitate counting of the rotations, one of the hollow cups is painted white and the others dark green. The spinner is mounted on a pivot at the end of a staff approximately 1.60 m long. The device may be equipped with a counter and an instantaneous electric transmitting system making it possible to transmit the wind speed data to a remote receiver; this is the model shown in Fig. 187.

The Jules Richard portable anemometer (Fig. 190).

This device consists of an extremely light and strong aluminum spinner which is able to operate under very low as well as very high air speeds without deforming, due to the shape of the blades. The shaft, a perpetual screw, meshes with a small wheel whose shaft is long enough to transmit its motion to an integrating counter contained in a hand-held watchcase.

In contrast to anemometers with counters placed in the center of the spinner, this arrangement has the advantage of producing no eddies and leaving a completely free space for the passage of the air.

To take measurements, the disengaged anemometer is carefully oriented in the direction of the air current. Care is taken to place the needles of the counter at zero, or merely to note the figures indicated. The spinner is engaged with the counter by pressing with the finger on lever A; at the same time, the starting time is noted on a watch with second hand. The anemometer is allowed to rotate for 10, 20 or 30 seconds, or even a minute, and the number of meters is read directly from the dial.

In the model with a second-counter, this counter, first set at zero, automatically goes into operation when the anemometer is started.

Fig. 188 shows a Richard anemometer equipped with an automatic rudder, designed for permanent installation in a meteorological station or semi-permanent installation to analyze the wind system in an area being considered for the installation of a wind motor. In this case the assembly is /257
connected to a recording receiver by electric wires powered by a storage battery, as shown in Fig. 191. Other assemblies including a rudder-anemometer and a system for recording the direction and speed of the wind may also be constructed. However, these assemblies, whose cost is fairly high, are used only for meteorological stations.

The GalDaloz portable pendulum anemometer

This anemometer (Fig. 193) is composed of a pendulum consisting of an aluminum sphere which oscillates within the plane of a graduated quadrant; each graduation gives a wind speed in m/sec. This quadrant is mounted on a rod which passes through the sleeve of the assembly. The bottom of this rod is mounted on a pivot, and the top on a ball bearing.

The assembly orients itself automatically to the wind; a counterweight attached to the rod brings the center of gravity of the moveable assembly over the axis of the rod. The sleeve of the assembly is designed so that it can be 258
disassembled to make the anemometer more compact for transport.

This anemometer has the fundamental characteristics of a reference:

1. Its graduations do not depend on any special coefficient.

2. Its readings are always the same, comparable to each other and comparable to those of another instrument of different dimensions built on the same principles.

Finally, it is easy to reproduce since its dimensions and graduations can be determined completely by calculation.

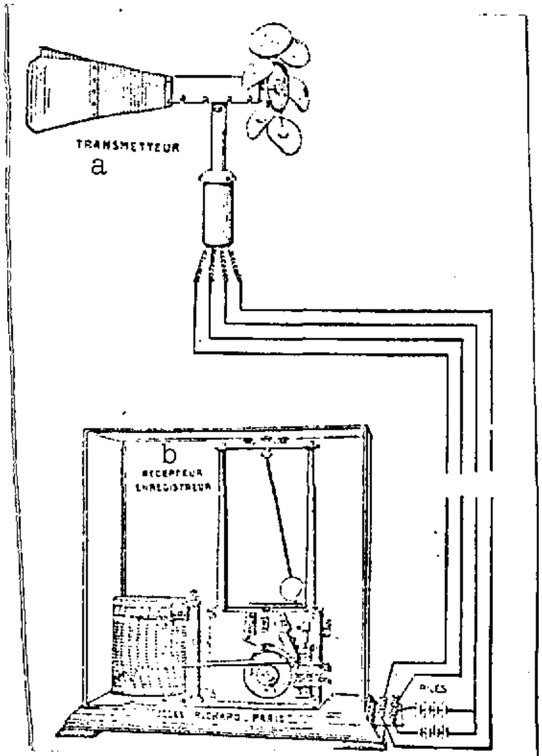


Fig. 191. Installation of a "anemo-kinemograph" of average wind speed with a clock indicating every 5,000 m of wind (J. Richard)

Key: a. Transmitter
b. Receiver/recorder
c. Batteries

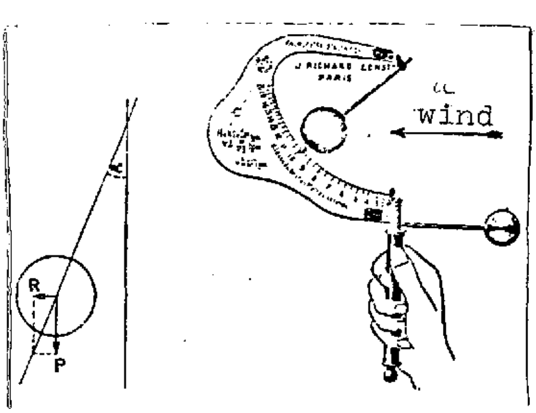


Fig. 192-193. The Daloz anemometer

If an extremely light hollow sphere is allowed to drop in free fall from a high point in a perfectly calm atmosphere, the speed at which it falls will first increase and then tend toward a constant speed which is termed the limit rate of descent v.

The limit rate of descent depends solely on the weight and volume of the hollow sphere. That used in the assemblies constructed by the Jules Richard Company has a limit rate of descent of approximately 10 m/sec which is obtained after 14 m of fall, plus or minus 1 cm.

For this period of descent, the effect of the air R is equal to the weight P of the hollow sphere, and the following may be written (Fig. 192):

$P = R = KSv^2$ and as a result,

$$v^2 = \frac{P}{KS} \qquad (1)$$

However, if the sphere is suspended from a balanced rod and exposed to a wind of speed V, the pendulum formed in this way will deviate from the vertical by a given angle α, as shown in Fig. 192. As it moves in this way, the hollow sphere is subjected to two forces, its own weight and the thrust of the wind; these two forces produce a resultant whose direction is an extension of the suspension rod. As a result: /259

$$R = KSV^2 = P \tan \alpha,$$

and consequently,

$$V^2 = \frac{P}{KS} \tan \alpha.$$

By replacing $\frac{P}{KS}$ with its value v^2 given by Eq. 1, one obtains:

$$V^2 = v^2 \tan \alpha \qquad (2)$$

which yields the speed V as a function of the limit rate of descent v.

At $\alpha = 45°$, $\tan \alpha = 1$ and $V = v$.

This means that the speed which causes the sphere to deviate 45° is precisely equal to the limit rate of descent of the sphere.

One can see from the preceding that the exact graduation of the assembly has been determined; to do so, it is sufficient to enter the values of V determined by Eq. 2 at the vertices of angles $\alpha1$, $\alpha2$, $\alpha3$, etc.

Bell Anemograph (F. M. B. System) (Courtesy of the Aéra Company, Paris).

This device, shown in Fig. 194, is derived from the recorders used to measure the flow rates of industrial gases.

It consists of two parts:

1. An antenna, which should be placed atop a pole in an area as free of surrounding obstacles as possible.

2. The receiver/recorder connected to the antenna by two systems of pipes which should be as straight and direct as possible and may be constructed of iron central heating pipes.

The antenna consists of a pivot attached to the supporting post by a sleeve and serving as a shaft for a swiveling head. The latter is equipped with a dynamic pressure inlet and a static pressure inlet which are kept in the eye of the wind /260 by means of a rudder. The pipes transmit these pressures to the receiver which is responsible for converting them into speeds.

The receiver is a bell manometer composed of a tank A containing a moving bell B connected to a pen C which enters the motions of the bell on a recording cylinder D 150 mm in diameter.

The inside of the bell B receives the dynamic pressure, while the outside, that is, the free part of the tank, which is kept impervious by a small hydraulic joint E, communicates with the static pressure inlet.

When the wind acts on the antenna it provokes a difference between these pressures H-H' = $V\,\frac{V^2 d}{2g}$; the bell would rise to its possible level in response to this pressure difference were it not for a balanced float which is buoyed up and weighs down the bell as it attempts to rise.

Thus the bell finds an equilibrium position for each pressure differential, and the tracing produced by the pen makes it possible to adjust the successive pressure values, that is, the speed V. A suitable shape for the flow makes it possible to choose a uniformly decreasing scale such that the speed graduations are equidistant.

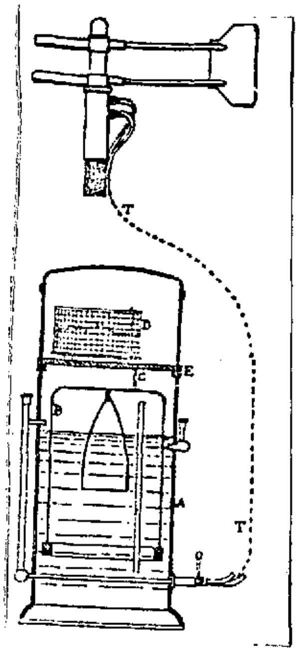


Fig. 194. Bell anemograph (Aéra Company)

The sensitivity of the device is quite high, given the cross section of the bell and the fact that it moves without mechanical friction or play.

Finally, the simplicity of the parts and their maintenance, which merely consists in maintaining the correct water level in the bell and the joint at the cap, permits wide distribution of this device.

The graduations are from 2-25 m/sec. The recording cylinder makes a complete rotation in 24 hours.

Calculation of wind pressure

Here the formula is as follows:

$$P = K\frac{d}{g}\,sV^2,$$

in which d is the weight of a cubic meter of air, which varies with temperature: 1.193 kg at 0° and 1.186 kg at 15°. These weights are measured at the mean atmospheric pressure of 760 mmHg.

g is the acceleration of gravity, which is 9.81 at sea level and decreases in proportion to altitude;

s is the area in square meters struck perpendicularly by the wind; /261

v is the wind speed in meters.

Various values for the coefficient K are assigned by different investigators:

Aubuisson assumes: $K\frac{d}{g} = 0.135$.

Ferret and Goupil: 0.0622.

Boulvin: 0.122.

If the pressure is not normal to the surface struck by the wind, these computations must be performed on a projection of this surface onto a plane perpendicular to the direction of the wind, or it must be multiplied by cos ϕ, ϕ being the angle between the surface considered and the direction of the wind.

According to the experiments of Langley and Colonel Renard and the Eiffel experiments, K should fall between 0.7 and 0.8. In these calculations, K will generally be assumed equal to 0.8, which yields

$$K \frac{d}{g} = 0.104.$$

Measurement of wind power

In England and Germany, the Beaufort scale is used to estimate the power of wind:

Wind speed in m/sec	Wind speed in mph	Beaufort scale	Wind pressure per m^2	Characteristics	Visible effects
1.5-3	5		0.5 kg	Slight breeze	Pleasant stirring of air
4 to 5	11	1	2.7 kg	Breeze	Movement of leaves
6 to 7	15	2	5.0 kg	Moderate breeze	Bending of shrubs and branches

[Table continued on next page]

[Table continued]

Wind speed in m/sec	Wind speed in mph	Beaufort scale	Wind pressure per m^2	Characteristics	Visible effects
8 to 9	20	3	8.0 kg	Strong breeze	Movement of trees
10 to 11	22	4	13.0 kg	Moderate wind	
12 to 14	30	5	19.0 kg	High wind	Breaking of shrubs and small branches
15 to 16	34	6	27.0 kg	Light storm	
17 to 19	40	7	40.0 kg	Storm	Breaking of large branches and trees
20 to 23	50	8	56.0 kg	Heavy storm	
24 to 28	58	9	76.0 kg	Violent storm	
29 to 33	67	10	103.0 kg	Hurricane	Complete destruction
34 to 39	80	11	137 kg		
40	90	12	195		

In France the effects of wind are estimated according to the following table, after Aubuisson, who computed them by the formula $P = 0.135\ SV^2$.

/262

	Speed in m/sec	Pressure in k/m^2	Effects of wind
Extremely light wind	1	0.13	No motion of leaves
Light breeze, starting of windmills	2	0.54	Slight agitation of leaves
Brisk breeze or wind	4	2.17	Slight stirring of branches
	6	4.87	

[Table continued]

[illegible]	Speed in m/sec	Pressure in k/m^2	Effects of wind
Moderately brisk wind suitable for windmills	7	6.46	Bending of small branches
Strong breeze	8	8.67	Swaying of branches
Brisk strong wind suited for sailing	9	10.97	Bending of branches
Extremely strong breeze	10 12	13.54 19.50	Bending of poplars
Extremely high wind	15	30.47	Breaking of small branches
Rough wind	20	54.16	Breaking of average-sized branches
Storm	24	78	Breaking of strong branches
Hurricane	30 36	122 177	Breaking of trees and damage to roofs
Severe hurricane	45	274	Large trees uprooted and roofs torn away

Some exceptionally strong hurricanes and cyclones have produced winds at speeds of 60-70 m/sec, representing a pressure of 500 kg/m^2. The structure of wind motors and the pylons on which they are mounted must be built to withstand these extremely rare, but possible wind speeds.

TABLE OF USABLE WINDS, AFTER THE TABLES PREPARED BY THE BERLIN METEOROLOGICAL INSTITUTE

One year = 365 days x 24 hours = 8,760 hours

Wind speed	Wind speed	Number of hours per year
	2-2.9 m/sec	831
	3-3.9 m/sec	1,350
	4-4.9 m/sec	1,661
	5-5.9 m/sec	1,722
	6-6.9 m/sec	1,287
	7-7.9 m/sec	868
	8-12 m/sec	720

Total usable winds: for.........8,439 hours per year

At speeds of more than 12 m/sec the vanes of the windmill should be turned aside.

OBSERVATIONS MADE OVER FIVE CONSECUTIVE YEARS BY THE OFFICIAL OBSERVATORY OF SAINT-MAUR PARK (CLOSE TO PARIS) /263

Number of hours during which the wind speed is higher than 2.50 m/sec

	Jan.	Febr.	March	April	May	June	July	August	Sept.	October	Novem.	Decem.	Total per year
Per day	16	17	18	18	16	15	13	13	13	14	14	16	
Per month	500	469	550	533	486	453	415	409	391	423	411	491	5,531

This table shows that there is an average of 450 hours per month during which an efficient wind motor would be able to furnish motive power; this amounts to 15 hours per day out of 24. The Paris area, in which these observations were made, is heavily shielded from the wind by a large number of hills.

In Normandy, in northern France and in the valleys of rivers such as the Rhône, the Lower Seine, the Loire and the Gironde, winds are stronger and the average number of usable hours is close to that observed in Berlin, given in the preceding table.

This average would be considerably increased on high plateaus and wide plains.

OBSERVATIONS OF WIND SPEED IN DIFFERENT AREAS OF FRANCE MADE OVER TEN CONSECUTIVE YEARS

	0-4 m/sec wind	4-8 m/sec wind	8-12 m/sec wind	Winds of more than 12 m/sec
Besançon	70 %	25,5 %	2,5 %	2 %
Bordeaux-Floriac	66,4 %	28,3 %	2,3 %	3 %
Brest	21,9 %	56,6 %	18,3 %	3,2 %
Clermont-Ferrand	57,5 %	27,4 %	9,8 %	5,3 %
Dunkerque-Sémaphore	33,4 %	36,2 %	18,7 %	11,7 %
Lyon Saint-Geniès	69,8 %	27,4 %	0,8 %	2 %
Marseille	58,1 %	32,5 %	7,4 %	1,9 %
Nantes-Petit Port	60,8 %	31,8 %	4,4 %	3 %
Paris-Parc St-Maur	60,2 %	29,9 %	6,7 %	3,2 %
Perpignan	54,4 %	36,4 %	5,4 %	3,8 %
Toulouse	55,3 %	35,4 %	7,4 %	1,9 %

[Commas should be read as periods, in this table and in the one below. -- Trans.]

Tests were made over ten consecutive years in Cuxhaven, at the mouth of the Elbe (Germany). According to Rühlmann, the results were as follows: /264

Wind speeds in m/sec	0 to 1,13	1,13 to 2,86	2,86 to 4,29	4,29 to 5,72	5,72 to 7,15	7,15 to 8,58	8,58 to 10,01	10,01 to 11,44	11,44 to 12,87	12,87 to 14,30	14,30 to 15,73
No. of days per year for which winds occur	21	77	90,1	77	47,8	25,1	11	5,3	1,4	0,4	0,1

According to this table, wind speeds of more than 5.70 m/sec occur during only 1/4 of the year, while the wind is above 2.86 m/sec and is therefore usable for 3/4 of the year.

Commander Riet has made a special study of the use of wind motors in Algeria. The following remarks were taken from a presentation made by him to a conference of the Algerian Agriculturist's Association on June 22, 1926.

"Actually, although its speed varies, wind is constantly available. The best indicator of its direction is the direction of movement of clouds. If it meets an obstacle, it turns aside in concentric circles. The radius of each of these circles is approximately six times the width of the obstacle at the point at which it is encountered.

For example, an airstream broken up by its impact with a wind wheel 5 m in diameter will reform only after it has traveled 5 x 6 x 2 = 60 m beyond the windmill. A second wind motor could not be placed within this distance from the first without the risk that the two assemblies would hinder each other's operation.

The average wind speed needed to drive a wind motor is between 2.50 and 8 m/sec.

Now, airstreams retain their optimum intensity and regularity at high altitudes, away from contact with the ground and generally in areas without any obstacles likely to slow them down or deform or disperse them. These types of areas include the seacoast, broad plains, high barren plateaus and mountain peaks.

Due to these considerations, the hot dry climate of North Africa, with intense sunshine and extremely marked temperature differences between day and night, plus a long seacoast and a high average altitude, should make this country ideal for /265
the use of wind energy to compensate for its lack of fuel and hydraulic power.

This prediction has been fully confirmed by the observations made at the Algerian Meteorological Institute, whose eminent director, Mr. Lasserre, has been kind enough to supply me with information in this regard.

These observations were made over a period of close to ten years (from January 1, 1916 to September 30, 1925); 19,363 observations were made and these may be broken down into:

4,374 relative to inadequate speeds of less than 2.50 m/sec
1,326 relative to excessive speeds of more than 8 m/sec — that is, 5,700 on unfavorable wind speeds
13,663 relative to favorable wind speeds

The percentage of usable speeds to observed speeds is thus greater than 70%, which represents 17 hours of favorable wind out of 24.

The average wind speed was 5.38 m/sec.

These results were confirmed, with a slight improvement, by tests performed at an altitude of 500 m at the Hussein-Dey Airfield and the Algiers Airport over a period of close to five years.

The probability of operation of a wind motor was found to be 78% or 18 out of 24 hours.

The average wind speed in meters per second was 5.66.

We might also mention, for the record only, due to the short time for which the observations were made (2 and 5 months respectively), the data obtained at the La Sénia and Sétif airfields.

Field	Altitudes	%	per 24 hp	Average speeds
La Sénia	200 meters	59	14 hours	5.42 m
	500	41	10 hours	5.92 m
Sétif	500	no	data available	6.26 m
	1,000	no	data available	7.30 m

These data seem to be overly favorable for Algeria compared with those for the Paris area, where tests have shown the certainty of operation for a wind motor without extended idle time to be: /266

"Probability of operation: 63% or 15 hours out of 24.
"Average wind speed in m/sec: 3.16."

Wind variation

These variations, both in speed and direction, occur so quickly and are of such amplitude that, no matter how sensitive the orientation assembly may be, there is always a point at which the orientation of the wind motor is defective. Thus the windmill undergoes stress for which it was not designed and is destroyed. /267

To reduce this disadvantage to a minimum, assemblies are usually designed so that they start to operate under a wind speed of 5-6 m/sec and cease to offer any airfoil surface once the wind speed exceeds 10 m/sec.

Mr. Lafond, a Montpellier designer, has transmitted to us the observations he has made on variations in wind (Fig. 195).

Graph 1 shows variations in the direction of wind; it may be seen that these are extremely fast and may reach considerable amplitudes. Graph 2 indicates the speed variations of an especially constant wind, and graph 3 those of a highly variable wind.

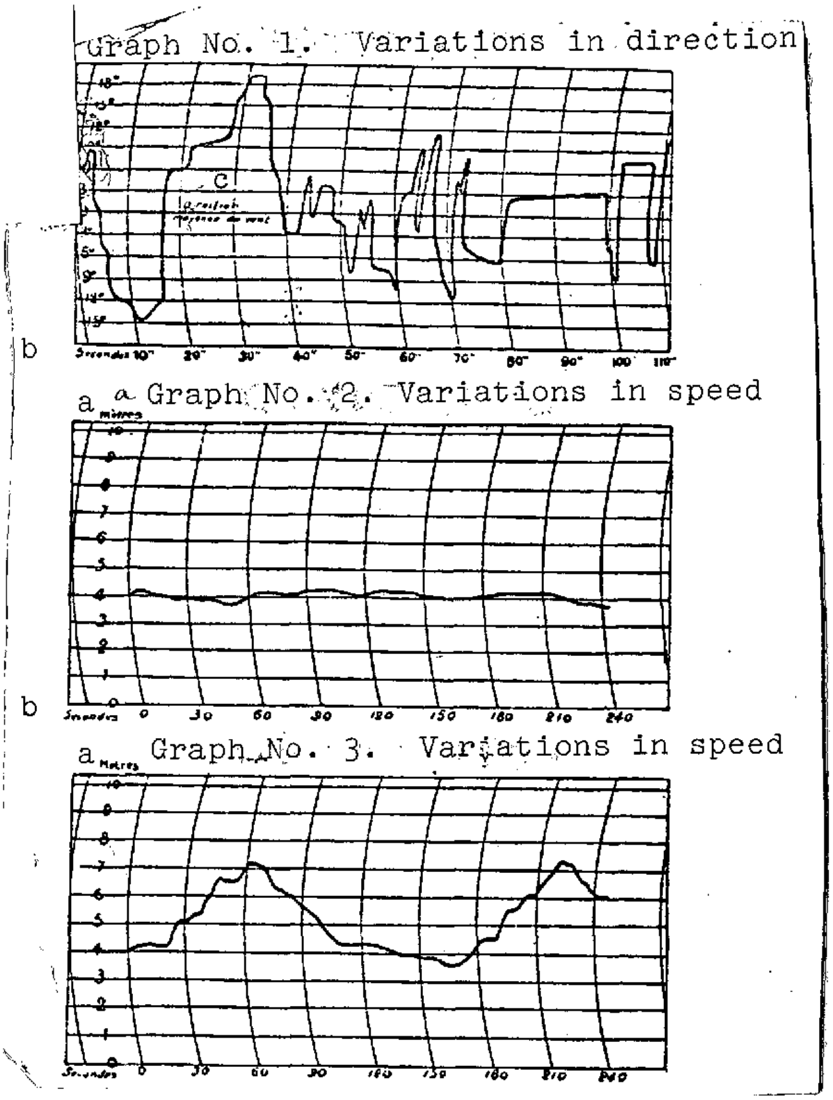


Fig. 195. Variations in wind direction and speed

1. December 9, 1926, direction NE
2. March 17, 1927, direction SSE
3. April 8, 1927, direction NNE

Key: a. Meters
b. Seconds
c. Average wind direction